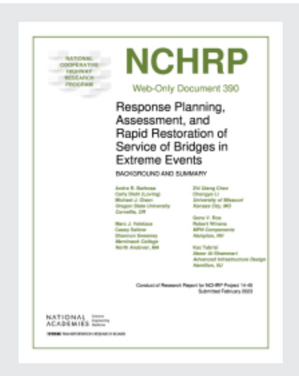

Response Planning, Assessment, and Rapid Restoration of Service of Bridges in Extreme Events: Background and Summary (2024)

DETAILS

255 pages | 8.5 x 11 | PAPERBACK

ISBN 978-0-309-72133-2 | DOI 10.17226/27813

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SUGGESTED CITATION

National Academies of Sciences, Engineering, and Medicine. 2024. *Response Planning, Assessment, and Rapid Restoration of Service of Bridges in Extreme Events: Background and Summary*. Washington, DC: The National Academies Press. https://doi.org/10.17226/27813.

NCHRP

Web-Only Document 390

Response Planning, Assessment, and Rapid Restoration of Service of Bridges in Extreme Events

BACKGROUND AND SUMMARY

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Conduct of Research Report for NCHRP Project 14-45
Submitted February 2023

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed, and implementable research is the most effective way to solve many problems facing state departments of transportation (DOTs) administrators and engineers. Often, highway problems are of local or regional interest and can best be studied by state DOTs individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation results in increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

Recognizing this need, the leadership of the American Association of State Highway and Transportation Officials (AASHTO) in 1962 initiated an objective national highway research program using modern scientific techniques—the National Cooperative Highway Research Program (NCHRP). NCHRP is supported on a continuing basis by funds from participating member states of AASHTO and receives the full cooperation and support of the Federal Highway Administration (FHWA), United States Department of Transportation, under Agreement No. 693JJ31950003.

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CONTENTS

NCHRP Web-Only Document 390 contains the Conduct of Research Report for NCHRP Project 14-45 and accompanies *NCHRP Research Report 1098: Guide for Response Planning, Assessment, and Rapid Restoration of Service of Bridges in Extreme Events.* Readers can read or purchase *NCHRP Research Report 1098* on the National Academies Press website (nap.nationalacademies.org).

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Summary

Extreme events, such as hurricanes, tornados, flood, earthquakes, fire, and collisions, pose a threat to the transportation infrastructure that millions of people depend on daily. Limited budgets, lack of resources, and large inventories challenge state departments of transportation (DOTs) and their ability to adequately prepare for an extreme event, execute a response, and restore service to bridges following an extreme event. The nation's aging bridge infrastructure further compounds the challenges facing state DOTs.

Few state transportation agencies have well documented planning and restoration of service procedures for extreme events and approximately half of state transportation agencies have informal or no procedures. Furthermore, very large-scale extreme events, such as hurricanes or earthquakes, are likely to cross state borders and rapidly deplete local resource. Neighboring states are often needed to assist in the response efforts. Guidelines that define a common approach to extreme event response for bridges are important to improve the resilience of highway networks and our communities.

The National Disaster Recovery Framework (Homeland Security 2016) identifies three phases of extreme events: pre-event planning, response, and recovery. These three phases can be described as occurring at separate times in the extreme event cycle: before, during, and after an extreme event. Careful preparation of procedures for these phases is needed to create a resilient highway network. This research developed a guide for the three phases of an extreme event based on existing literature from state and federal transportation agencies, scholarly journals, and conference proceedings.

The procedures in the guide use a "First You Plan" approach. Careful pre-event planning and coordination across internal departments, stakeholders, and neighboring jurisdictions is emphasized during this planning phase. Important aspects of planning include preparing for the response and recovery phases, performing what-if scenarios, identifying funding sources, developing chains of command, and stockpiling resources at predesignated locations. Mock training and other training exercises help identify gaps in response steps, and ensure all personnel are familiar with the response and rapid restoration procedures.

During the response phase of an extreme event, state DOTs need procedures to rapidly mobilize inspection teams to assess damages. A four-stage assessment process (Fast Reconnaissance, Preliminary Damage Response, Detailed Damage Response, and Extended Investigation) is recommended to quickly deploy assessment teams and prioritize bridges for repair. Uniform procedures for collecting, reporting, and processing the damage level of the bridge structures in the region is important for situational awareness and to inform additional assessment stages and repair decisions. Harnessing new technologies such as unmanned aerial systems (UASs) equipped with lidar and cameras help identify damage to bridges in unsafe or difficulty to access areas. These advanced tools increase personnel safety and assist in providing a digital damage map of the affected region.

The recovery phase begins once structures have been assessed and can occur in parallel to response phase activities if appropriate resources are available. Repairs are prioritized based on an impact analysis of the transportation network and rapid restoration solutions can be selected and implemented. Bridge owners can use rapid procurement methods to expedite repairs. Temporary solutions, such as supplemental shoring or modular bridges, should be considered to restore service to partial or full capacity while permanent solutions are being planned. Prefabricated components and the use of accelerated bridge construction (ABC) techniques can be suitable options to reduce disruption of service to heavily impacted regions and provide high-quality solutions that will serve as permanent repairs.

Reflection and documentation of lessons learned from an extreme event is an important component of the recovery phase. Lessons learned from previous events are documented in the form of case studies as

part of this project. Templates and tools developed through this research enable new case studies to be generated by state DOTs using a similar format for consistency. These case studies are important to develop a record of institutional knowledge and to inform updates to procedures in preparation of future extreme events. These case studies can be shared both within and across agencies to benefit a broad segment of the general public.

A Bridge Assessment and Rapid Restoration Tool (BARRT) was developed to assist state DOTs in implementing the guide. BARRT is an interactive Microsoft PowerPoint presentation and has a website-like feel. BARRT uses visual basic for application (VBA) code to connect between to Microsoft Excel and Word files. Users can view content mentioned in the guide and link to additional resources to aid in response planning, assessment, and rapid restoration directly from BARRT. By organizing procedures in one location, state DOTs can select procedures that are commonly used across the country and are appropriate for their unique circumstances. BARRT is also a repository for case studies to enable agencies to maintain institutional knowledge. State DOTs can customize BARRT to fit their specific needs. Integrating the guide developed in this project with current agency practices will encourage innovation within the agency and promote resiliency across the nation.

Chapter 1: Background

1.1 Background and Problem Statement

Extreme events resulting from natural or other disasters, such as fire, flood, earthquakes, tornados, and hurricanes, can cause damage to bridge structures and impact the safety of motorists and the public. Some state departments of transportation (DOTs) have adopted procedures for response planning, assessment, and rapid restoration of service of bridge structures. However, these processes tend to focus on a single hazard and may not address the full range of needs for different types and extents of possible events.

Comprehensive, rational and a practical guide for response planning, assessment, and rapid restoration of service of bridge structures in extreme events are needed to maintain the safety of the general public. The guide addresses the needs of all state DOTs for all extreme event hazards and must be prepared in a manner to facilitate consideration and adoption by the American Association of State Highway and Transportation Officials (AASHTO). This guide would help state DOTs as well as other transportation agencies find rapid repair solutions for damaged bridge structures caused by extreme events and improve the resilience of our communities.

1.2 Research Objective

The primary objectives of this project were to develop:

- Guide for response planning, assessment, and rapid restoration of service of bridges in extreme events.
- Tools to facilitate implementation of the guide by state DOTs.

1.3 Research Scope and Approach

This project was divided into two phases. The first phase focused on information collection through a literature review to define the state-of-the-art and state-of-practice in planning, response, and rapid restoration of service of bridges in extreme events. Sources for this review consisted of DOT manuals, policies, and guides in addition to scholarly journals and conference proceedings. A questionnaire was administered to all state DOTs to collect additional insight on the current practices of state DOTs and to determine the maturity levels of these agencies to develop a guide that would answer their unique needs. Both the literature review and questionnaire reviewed procedures centered around response planning, assessment, and rapid restoration of service of bridges. Technologies used, methods followed, and case study examples were collected and organized. These identified procedures were synthesized and evaluated, and the project team developed recommendations for the guide.

During the second phase of the project, the project team developed the guide based on the recommended procedures from Phase 1. The guide was compiled into a two-column format to conform to the requirements of AASHTO. In addition, the project team developed an interactive tool to complement the guide and facilitate implementation of the guide by state DOTs. A comprehensive final report (this document) summarizes the overall project, the main findings and share the results of this research project.

1.4 Organization of the Report

NCHRP Project 14-45 includes four parts. Part 1 (this document) provides background on planning, assessment, and rapid restoration of service of bridges in extreme events. This part also provides an overview of the guide and the implementation tool. This part contains the following chapters:

- Chapter 2 presents a summary of the state-of-art and state-of-practice for planning, assessment, and rapid restoration of service of bridges identified through the extensive literature review and questionnaire.
- Chapter 3 evaluates the procedures discussed in Chapter 2 and provides recommendations for the proposed guide.
- Chapter 4 provides an overview of Part 2 (published as *NCHRP Research Report 1098: Guide for Response Planning, Assessment, and Rapid Restoration of Service of Bridges in Extreme Events*).
- Chapter 5 describes the implementation tool, Bridge Assessment and Rapid Restoration Tool (BARRT).
- Chapter 6 presents conclusions of planning, assessment, and rapid reaction of service of bridges in extreme events.

The main text is succeeded by references, list of acronyms, a glossary and an Appendix that includes the questionnaire results.

Parts 2 through 4 are provided separately:

- Part 2: *NCHRP Research Report 1098: Guide for Response Planning, Assessment, and Rapid Restoration of Service of Bridges in Extreme Events* – —this document defines recommended procedures for state DOTs to prepare for and respond to an extreme event.
- Part 3: *Bridge Assessment and Rapid Restoration Tool* (BARRT)—this is an interactive PowerPoint and associated files that will assist DOTs in implementing the recommendations described in Part 2.
- Part 4: *User Manual for the tool*—this document describes how to use BARRT. In addition, this document explains how BARRT can be revised by DOTs to suit their specific needs and to include extreme event procedures currently in use in their agency or other agencies. The tool (Part 3) and user manual (Part 4) can be found on the National Academies Press website (nap.nationalacademies.org) by searching for *NCHRP Research Report 1098: Guide for Response Planning, Assessment, and Rapid Restoration of Service of Bridges in Extreme Events*.

Chapter 2: State-of-the-Art and State-of-Practice

2.1 Introduction

This chapter summarizes the key findings from a detailed literature review and questionnaire to determine the current state-of the-art and practice pertaining to planning, assessment, and rapid restoration of bridges during extreme events. The questionnaire and complete summary of the questionnaire responses are included in Appendix A and Appendix B, respectively.

A detailed literature review was conducted to identify procedures currently in use by federal, state, and local state DOTs for an extreme event. "Extreme events" included earthquakes, hurricanes and storm surges, floods, fires, tsunamis, collisions, and man-made events. Manuals, guides, policies, and research articles were the primary sources of information. Only publicly accessible materials are referenced.

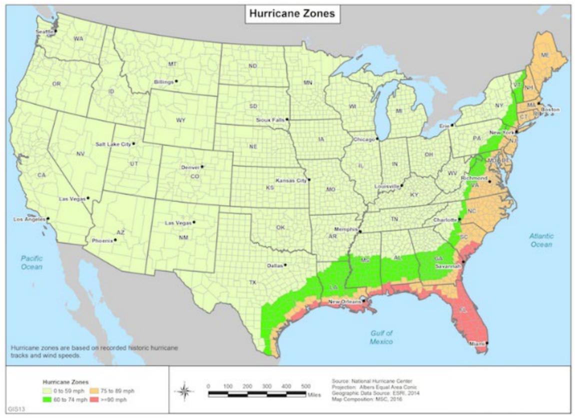
A questionnaire was administered from November 2020 to January 2021 and distributed to all 50 states departments of transportation (DOT) and the District of Columbia. This questionnaire supported the literature review and provided greater insight into current practices at the DOTs. Furthermore, the questionnaire generated ideas for case studies and identified other manuals and guides specific to each DOT. The questionnaire collected responses from 46 respondents representing 45 states plus the District of Columbia. Respondents represented a breadth of bridge personnel, ranging from maintenance, management, and designers who are actively involved in planning, assessments, and rapid restorations of bridges.

2.2 Planning

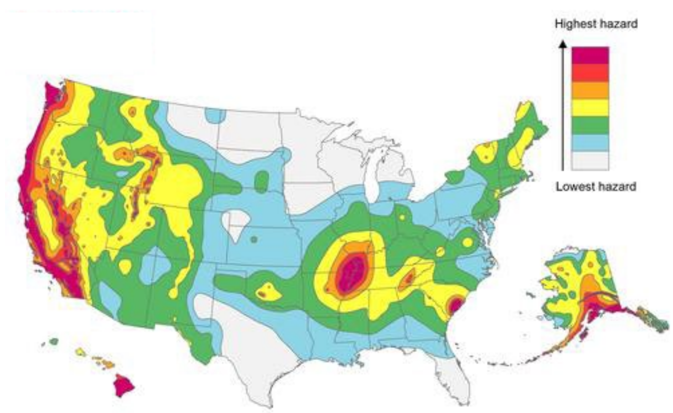
The planning phase of an extreme event includes all preparatory actions taken prior to an event. During the planning phase, state DOTs ready themselves by establishing clear chains of command, identifying vulnerable structures, understanding funding sources, and conducting hypothetical what-if analyses as training exercises for staff. Generally, planning procedures align with state emergency response plans, extreme event specific training for personnel was found to be minimal due to budget constraints. State DOTs are knowledgeable in identifying the extreme events that represent the largest hazard to their region, and some DOTs have developed a series of procedures to quicken responses and initiate assessments for these anticipated events. Events that occur less frequently, such as earthquakes or fires, pose challenges to state DOTs who do not regularly respond to these situations. A wide range of manuals, guides, and policies were reviewed and detailed herein. These documents covered a broad range of topics including: retrofits and other preventive measures, general coordination and communication methods, plus overviews of response techniques.

2.2.1 Anticipated Extreme Events

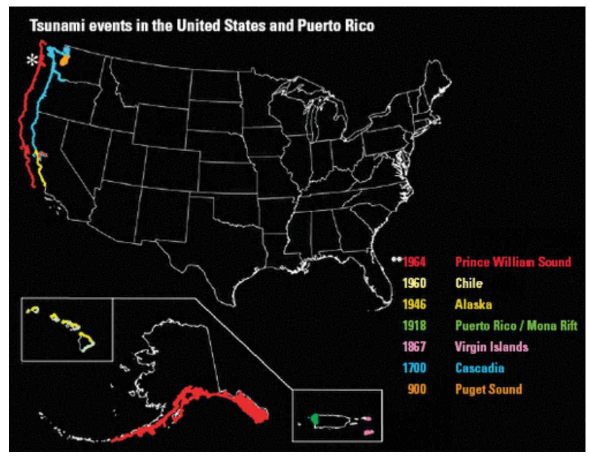
Geography and climate are major factors when it comes to anticipated extreme events for state DOTs. Some events, like collisions, fires, and floods can occur in every state. However, other events like earthquakes, tsunamis, and hurricanes tend to occur in specific regions of the United States.



(A) Hurricanes (Taylor 2017)



(B) Earthquake (USGS 2018)



(C) Historic Tsunamis (USGS 2020)

Figure 2-1. Threats of Emergency Events Across the USA

2.2.2 Coordination and Communication

2.2.2.1 Establishment of Command Center

Command centers are typically established across the State DOT's jurisdiction. The command center serves as the main headquarters during an emergency event, and is the source of all information gathering, planning, and response after such incident. First responders, inspectors, transportation agency personnel, and the public look to the command center for guidance and instruction. State DOTs emphasized the importance of these centers being well-established, well-stocked, and well-advertised, so in a time the situation on the ground is changing rapidly, it is clear where the governing authority is located. Furthermore, state DOTs indicated that emergency vehicles and other equipment are stored fully fueled in preparation for rapid deployment. From the sources of literature reviewed, key considerations for command centers are summarized in Table 2-1.

Table 2-1. Key Considerations for Command Centers

Considerations	Descriptions	Source(s)
Stockpiled Provisions	Food, water, other supplies; traffic control devices, temporary structures, and shoring	Illinois Department of Transportation 2010
Utilities	Chemical toilets, generators, heaters, and cooking stoves	Illinois Department of Transportation 2010
Predetermined locations	Regional DOT offices, fairgrounds, etc. Should have primary and secondary locations, Mobile command centers (trailers or vans).	Oregon Department of Transportation 2014; Illinois Department of Transportation 2010
Abide by state-identified procedures	Incident Command (IC) Model, National Incident Management System (NIMS) framework, Traffic Incident Management (TIM) protocol, etc.	Parra 2014

2.2.2.2 Assigning Responsibilities

Once a command center(s) is established, the priority shifts to assigning responsibilities to personnel. During an emergency event, multiple jurisdictions may be involved, so it is important for all stakeholders to be aware of the chain of command and understand their assigned tasks. In general, State DOTs indicated that local, county, state, and tribal groups should all work together to respond, assess, and repair/replace damaged structures, whether an event is widespread or local. Flowcharts, tables, and other organizational charts help convey hierarchy, assign roles, and provide a go-to source for contact information and the overall chain of command (HDR 2014, Nebraska Department of Roads Bridge Division 2020). These charts often identify key stakeholders and partnerships with community groups, faith-based organizations, and local businesses that can aid in the overall response and recovery process (Fraizer et al. 2020).

2.2.3 Funding

Some state DOTs are familiar with the funding resources available to them to aid in overall recovery. Common funding authorities are outlined in Table 2-2. Local funding options, like tolls and road taxes can supplement or replace state or federal funding as needed (Wang et al. 2014).

Table 2-2. Common Post-Event Funding Sources (Bye et al. 2013)

Funding Authority	Program	Description
Stafford Act Programs	FEMA Public Assistance (PA)	PA grants are FEMA's primary assistance program for state and local governments. These grants may be used to repair, replace, or restore disaster-damaged, publicly owned facilities and the facilities of certain private nonprofit organizations.
	FEMA Hazard Mitigation Grant Program (HMGP)	FEMA's HMGP provides grants for states to implement mitigation measures during recovery from a disaster and to provide funding for previously identified mitigation measures.
Other Federal Programs	U.S. Department of Housing and Urban Development Community Development Block Grants (CDBGs)	CDBG funds are generally allocated to states for housing and community development purposes. In recent years, this program has been a vehicle for delivering additional disaster aid to states with major disasters.

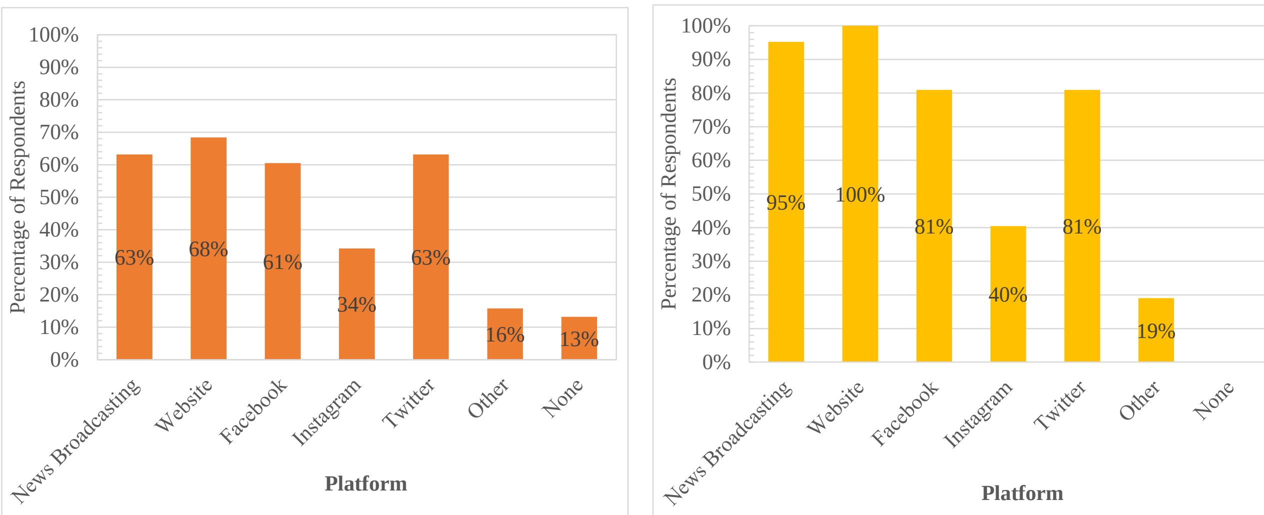
Funding Authority	Program	Description
	Economic Development Administration (EDA) Grants	EDA grants are available to regions experiencing sudden and severe economic dislocations such as those resulting from natural disasters. Funds can be used for infrastructure to support community economic development.
	Special Funding	Congress can enact special legislation to provide emergency funding. For instance, P.L. 109-87 authorized the Secretary of Transportation to make project grants for airports that incurred emergency capital costs because of Hurricanes Katrina or Rita.
U.S. DOT Programs	FHWA Emergency Relief (ER) Funds	ER is a special program from the Highway Trust Fund. Funds are available for the repair of federal-aid highways or roads on federal lands that have been seriously damaged by natural disasters over a wide area or by catastrophic failures from an external cause.
	Emergency Relief for Federally Owned Roads (ERFO)	ERFO provides funding and engineering services for the repair and reconstruction of roads in public lands after a natural disaster or a catastrophic failure. The following categories of roads are eligible: Forest Highways, Forest Development Roads, Park Roads and Parkways, Indian Reservation Roads, Public Lands Highways, Refuge Roads, Military Installation Roads, Corps Recreation Roads, Bureau of Reclamation Roads, and Bureau of Land Management Roads.
State Programs	State Disaster Emergency Funds	States typically have a Disaster Emergency Fund, regularly appropriated by the state government, which can be used to finance recovery efforts and to match grant dollars provided by the federal government. The amount of funds varies by state; states that are more vulnerable to disasters may place greater amounts of money in their Disaster Emergency Fund than states that have not typically been victim to many disasters. In most cases, if this funding is not enough, or the state requires additional recovery funding that cannot be acquired from other sources, the governor (or another similar state government official) has the authority to allocate additional state funding for recovery assistance.
	State Bond Initiatives	State and local bond issues are major vehicles through which state and local governments can finance public projects, especially project upgrades that are not eligible for FEMA's PA grant program. These bonds do not require a presidential disaster declaration. These public purpose bonds are used for roads, streets, highways, sidewalks, libraries, and government buildings. Bond funding can be used by state and local entities to pay the match portion of PA projects, as well as pay for upgrades.
Other	Private Insurance	The NTRS recommends that insurance coverage be evaluated prior to an event to ensure sufficiency and to understand the limitations of liability insurance policies in situations where people may need to be evacuated or temporarily displaced from their homes due to a transportation disruption.

2.2.4 Information Acquisition and Sharing

Primary forms of communication are heavily dependent on connectivity and services available post event. State DOTs rely on a mix of general communication devices, such as phone lines, radio communication, amateur radio, and computers (email, instant messaging, etc.). The use of repeaters can be deployed if communication towers are down, and other backup methods of contact should be established (Illinois Department of Transportation 2010).

To communicate with the public, many states use the 511-communication number to share information with travelers and those in the area. States such as Iowa use this service to issue road condition reports and maintain updates on closures and detours. Other electronic services such as the DOT website and social media (i.e., Twitter) are used to notify the public about an event. Apps and other push-notifications, such as AlertSeattle and Wireless Emergency Alerts (WEA), are notification systems that allow state DOTs to share alerts with citizens who are signed up with the program or are located within a specified radius of an extreme event (Davis 2020).

To gather information, state DOTs harness the power of crowdsourcing and social media. State DOTs tap into this wealth of knowledge to identify areas damaged after an extreme event, to verify damage, and to share information with the public (Department of Homeland Security and Technology 2014). If combined with a Geographic Information System (GIS) or other geospatial database, social media can be a powerful tool at identifying areas of concern and help with relief efforts. It can also be used to warn the public about evacuation routes, closures, and staging areas. Questionnaire respondents indicated that social media platforms (such as Twitter, Instagram, and Facebook) were some of the main methods to gather information from the public, but also to share information with the public (Figure 2-2).



A) Information Gathering / Crowdsourcing. N=38 ***B) Communicating Closures or Delays. N=42***

Figure 2-2. Technology Used by State DOTs

Other examples of crowdsourcing include apps such as Pulse Point, which can send out an alert if someone is in need of CPR, or “Did you Feel it?”, an app developed by the USGS to gather information on where people felt earthquakes. Crowdsourcing can be an important component to identify hazards. It is common for the public to be aware of an emergency before officials, and crowdsourcing can report findings quicker, possibly saving lives (Department of Homeland Security and Technology 2014).

2.2.5 Preventative Measures

The risk of damage to bridges during an extreme event can be reduced with good inspection/maintenance programs and targeted bridge retrofits. Inspection and maintenance programs repair deficiencies and reduce the likelihood of damaged due to an extreme event (Chavel & Tadlosky 2011). In addition to routine and cyclical maintenance programs, retrofits and other preventative measures can be used to better prepare bridges and culverts for extreme events. Common event specific retrofits are shown in Table 2-3.

Table 2-3. Common Extreme Event Retrofits

Common Retrofits or Repairs	Applicable Extreme Events	Source
Connection and element strengthening	Earthquakes, hurricanes	Buckle et al. 2006, Robertson et al. 2007
Energy dissipating devices	Earthquakes	Buckle et al. 2006
Base isolation systems	Earthquakes	Buckle et al. 2006, Alipour 2016
Dead load reduction	Earthquakes	Buckle et al. 2006
Shear keys	Earthquakes, hurricanes, and storm surge	Buckle et al. 2006, Robertson et al. 2007
Restrainer and bearing seat extensions	Earthquakes, tsunamis	Buckle et al. 2006, Kawashima and Matsuzaki 2012
Replacement of defunct elements	All	Buckle et al. 2006
Installation of scour countermeasures	Tsunamis, floods, hurricanes, and storm surge	Kawashima 2011, FEMA Region 10 2001, Skrocki et al. 2020, Suro et al. 2020
Larger vertical clearances	Collisions, hurricanes and storm surge, tsunamis	AASHTO 2008, New York State Department of Transportation 1996
Continuous superstructures	Earthquakes, hurricanes	AASHTO 2008
Solid or flat-bottom slabs	Hurricanes	AASHTO 2008
Widening of waterways or reduction in number of openings in bridge	Floods	Albert 2020
Replacing spread footings with piles	Floods, tsunamis, hurricane, and storm surge	Albert 2020
Replacement of fracture critical elements or structures	All	New York State Department of Transportation 1996
Clear waterway navigation	Collisions	New York State Department of Transportation 1996
Substructure protection systems	Collisions	Starcouriernews 2020
Installation of fire protection systems	Fire	National Fire Protection Association 2014
Continuous spiral reinforced columns and substructure elements	Earthquakes, man-made	Williamson et al. 2010
Seismic and blast-specific detailing	Earthquakes, man-made	Williamson et al. 2010

2.2.5.1 Establishing Baseline Conditions

State DOTs use many systems for storing and maintaining bridge records. Some state DOTs use long-term monitoring systems to detect small changes that may not be noticeable with visual inspection techniques (Collins et al. 2014, Salamone et al. 2012). A comparison can be made to previous bridge records and the existing conditions to help identify damage induced by the emergency event. These small changes can provide early indication of impending damage that ordinarily may go unnoticed in routine inspection. The use of long-term monitoring can reduce the lag time after an event for inspection, as data is available immediately. Furthermore, it can increase the resilience of the structure, as these methods are reliable approaches for data collection, and help DOTs make informed decisions about their infrastructure (Achillopoulou et al. 2020).

2.2.6 Implementation Preparation

In preparation for an extreme event, state DOTs require their personnel to complete any required certifications and training to better equip them with the tools needed to respond to an extreme event. Some topics for training or certification include (Nakanishi & Auza 2015, Oklahoma Department of Transportation 2017, and State of Minnesota Department of Transportation 2019):

- Traffic Incident Management (TIM)
- Emergency Management Accreditation Program (EMAP)
- HazMat (Nakanishi & Auza 2015)
- Hazards and Safety Training (Nakanishi & Auza 2015)
- National Response Framework (NRF) training
- General Drills on DHS, FEMA, and TSA protocols
- General Bridge Inspection
- General Bridge Inspector (options provided by NHI)
- Non-Destructive Testing Certification
- Confined Space (including air monitoring)
- Traffic Control
- Personal Protective Equipment (PPE)
- Under Bridge Inspection Vehicle /Snooper
- High Ropes/Overhead Powerlines

Some state DOTs garner information from sources like the Unified Response Manual (URM) that specifies the specific training requirements for emergency personnel (Parra 2014).

2.2.6.1 Assessment

Emergency assessments include both the emergency inspection and evaluation of a structure after an emergency event. Most state DOTs follow a multi-step emergency inspection process, which commences with an initial inspection or “first look”. These initial inspections are focused on prioritizing structures for response and identifying structures that warrant further investigation (Oregon Department of Transportation 2014, Alaska Department of Transportation and Public Facilities 2018). If indicated, structures then undergo a Level II Inspection within 72 hours of the extreme event occurring. These inspections provide a more detailed look at the structure and determine if it is safe or unsafe for use (Reed & Wang 1993, Ramirez et al. 2000, and Oregon Department of Transportation 2014). If determined unsafe, a Level III Inspection often follows. These inspections include on-site analysis, and nondestructive tests of the main structural members to aid in the load capacity evaluation. Specialized inspections like underwater inspections may be required to complete these in-depth analyses (Collins et al. 1989 and Illinois Department of Transportation 2010). The qualifications and level of training for the personnel performing the initial inspections vary depending on the inspection type and the agency. Routine training can be provided in these areas to reduce the time required for refresher training before assessment teams are deployed.

Evaluations based on the emergency inspections, like load rating or finite element models, are used by state DOTs to determine the load carrying capacity of a structure and to determine if repairs are necessary (HDR 2014, AASHTO 2018).

2.2.6.2 Route Alterations

State DOTs often develop pre-determined criteria for when to fully close or partially close a structure, establish detours, and/or shore a structure. Major connector routes (which may serve as evacuation routes) are mapped by state or federal agencies, which are prioritized for repairs to maintain traffic flow. These routes are published for easy access to the public and are also marked with signs (Eker & Crosset 2008. and Illinois Department of Transportation 2010). Contraflows and fall zones may be implemented to evacuate people and provide safety barriers around heavily damaged infrastructure (Davis 2020 and Fraizer et al. 2020).

Some states offer guidance to determine the best route alteration method. In Alaska, guidance is provided to maintenance and operations personnel on actions to take following a bridge assessment (see Table 2-4). Possible actions include closing the bridge to all traffic, close the bridge temporarily for until damages portions can be shored or keeping the bridge open. Additional consideration for closure and lane restrictions following an over height collision are shown in Table 2-5.

Table 2-4. Possible Bridge Assessment Actions - Close, Shore, or Open (Based on Alaska Department of Transportation and Public Facilities 2018. An update to the Field Operations Guide is planned and this table will be slightly revised)

Close	Close Temporarily	Open
Shoring or repairs not feasible	Shore, repair or restrict to reopen bridge	No shoring needed
Bridge is collapsed or impassible. Close to all traffic.	Damage is serious, but shoring repairs or restrictions would allow re-opening.	Based on inspection, the bridge should remain open.

Table 2-5. Considerations for Structure Closures or Lane Restrictions following an Over Height Collision (HDR 2014)

Restricting Traffic on the Bridge	Closing Traffic Lanes under the Bridge
• Extent of damage to supporting girder(s) • Location of damaged girder(s) with respect to traffic lanes • Structural redundancy (for example, the number of girders) • Ability to strengthen/stabilize structure • Ability to safely shift traffic lanes considering lane widths, average daily traffic, speed limit, and traffic direction • Availability of detour routes • Importance of traffic route	• Vehicles or payloads blocking lanes or impeding traffic flow • Debris on the road from vehicles/payloads or the bridge itself • Damage to the road surface under the bridge • Potential for additional debris to fall from the structure onto traffic • Instability of bridge or compromised structural integrity of the bridge • Potential of future over height collisions to cause collapse of damaged structure • Structure having the appearance of being unsafe so as to distract the travelling public • Displaced bridge members that intrude on vertical and/or horizontal clearance requirements

2.2.7 Technology

The questionnaire results indicated that agencies use a wide array of technologies for emergency inspections. Unmanned aerial systems (UASs), GPS/GNSS, water depth devices, and smart devices without specific apps were some of the technologies that agencies were most likely to use (Figure 2-3).

Agencies indicated that concerns like lack of funding, engineering review, and permitting were larger barriers compared to implementation of new technologies. Non-digital technologies like hard copy maps, forms, and other communication methods are still the preferred methods for many agencies and provide a level of redundancy when communication devices or other technologies may be down. Some states rely on specialized or custom tools (i.e., software, apps, or process flowcharts) for extreme event planning, assessment and rapid restoration of service. The tools currently used or desired by state DOTS are listed in Table 2-6.

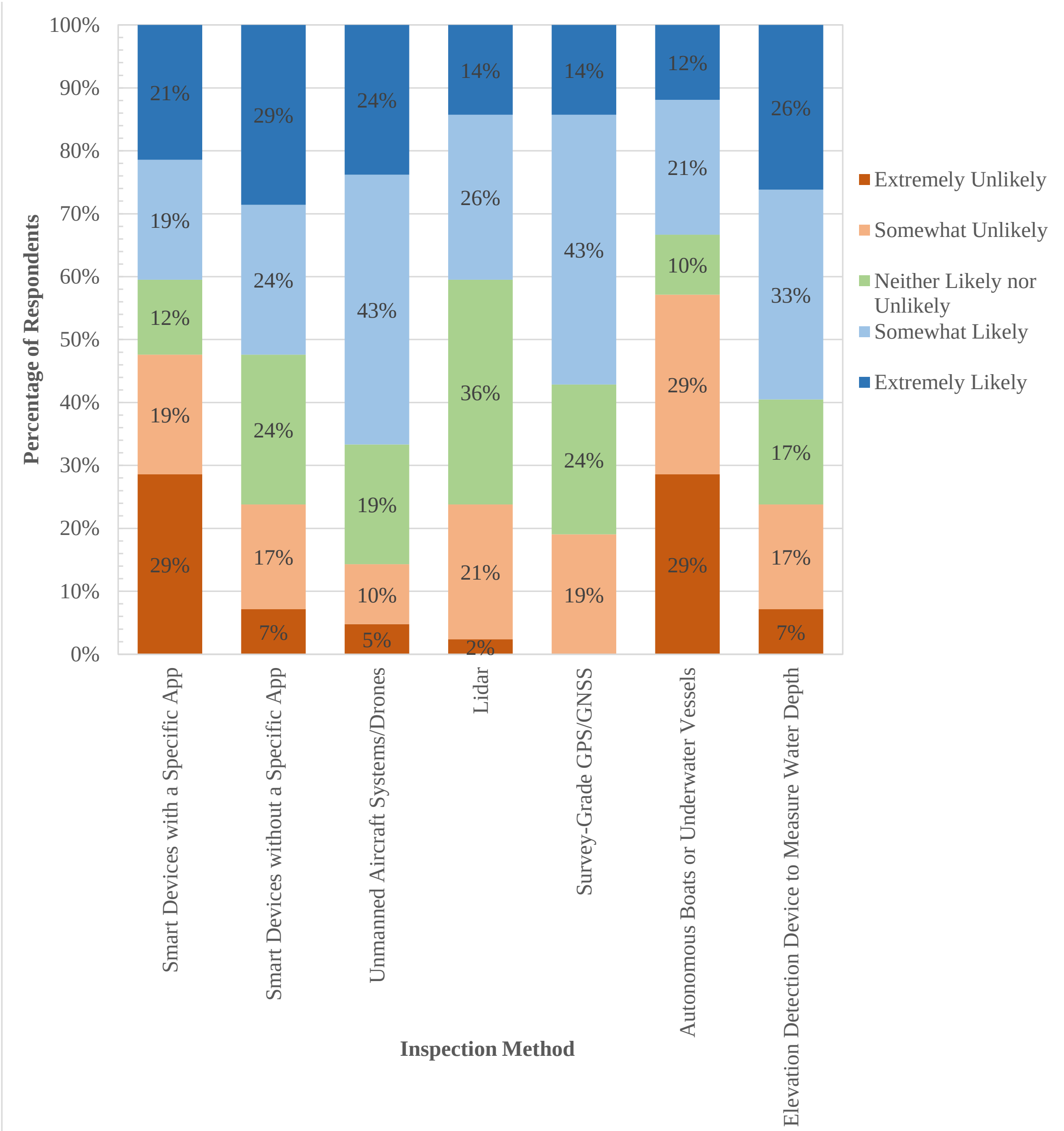


Figure 2-3. Technologies Used for Emergency Inspections by State DOTs. N=42 DOTs.

Table 2-6. Tools Currently Used or Desired by State DOTs for Extreme Events

Stage	Tools Used	Tools Desired
Planning	• BridgeWatch • Custom flowcharts	• Traffic impact tool that recommends

	• GIS mapping • Required equipment checklists • ShakeCast • Weather and traffic data reports	personnel and equipment needed to inspect numerous structures • First responder training similar to the training modules developed in *NCHRP Research Report 833*
Assessment	• Bentley AssetWise • BridgeWatch • Custom flowcharts • GIS mapping • In-house data collection software • Mobile Solution for Assessment and Reporting (MSAR) • Over height vehicle collision apps • RainShare • Remote control boats and underwater vessels • ShakeCast • Standard damage assessment forms and mobile device for electronic collection and reporting • Survey 123	• App that aligns with approach described in *NCHRP Research Report 833* • Inspection app similar to InspectX
Rapid Restoration	• Custom flowcharts • Library of standards and design tools • Library of working drawings for beam impacts and other repairs • Survey 123	• Cost estimators • Database of shoring options • Prioritization methods

2.3 Assessment

The assessment phase of an extreme event includes the mobilization of resources immediately following an extreme event and the subsequent inspection and evaluation of infrastructure to determine the extent of damage, prioritize work, and select restoration solutions. During this phase, state DOTs must deploy inspectors to conduct assessments of all impacted bridges and provide a plan of action for each impacted structure.

2.3.1 Inspection Coordination and Communication

2.3.1.1 Refresher Training

During the mobilization of inspection teams, state DOTs often provide brief 30-45-minute-long refresher training for their inspection crews. The goal of this training is to provide specific details about the extreme event that are unique to the situation (geography, current conditions, prioritization, etc.), and to provide a good reminder of the agency's required documentation, procedures, and practices. Typically, the refresher training is provided to individuals who are already familiar with the State DOT expectations, and is only meant to provide a reminder, not to serve as a substitute for pre-event planning and training.

State DOTs may provide required resources during this refresher training, like assessment forms, flowcharts, or maps (New York State Department of Transportation 2020 and Washington State Department of Transportation Bridge Preservation Office 2020). Information for uploading data (photos, notes, sketches, or other information), should also be included in refresher training courses (Mississippi Department of Transportation n.d., Olsen et al. 2016).

2.3.1.2 Inspection Resource Needs

State DOTs have various approaches for determining the number of inspection teams needed for an extreme event. Many base this decision on the type and severity of an extreme event. In Washington State, inspection crews are identified for earthquakes based on the earthquake magnitude, as shown in Table 2-7.

Table 2-7. Anticipated Inspection Requirements Post-Seismic Event (Reed & Wang 1993)

Event	Rationale / Source	Number of Bridges Used to Calculate Team Leaders	Number of Team Leaders Required
Moderate	All bridges with Structural Vulnerability Rate SV > 0	789	53-87
Major	Based upon Modified Mercalli Map	1129	76-124
Great – assume only districts 1,3 and 4 affected	All bridges in districts 1, 3 and 4	1418	95-156
Great – assume all districts affected	All bridges in the database (districts 1-5)	1635	110-181

2.3.2 Implementation Preparation

2.3.2.1 Prioritizing Structures for Assessment

Priority routes and bridges are often identified during the pre-event planning phase. However, many state DOTs have developed a system to adjust pre-planned priorities to consider the unique aspects of a real extreme event. These considerations include a structure's location with respect to Lifeline Routes, as these routes should be opened to traffic within 72 hours of the emergency event, if feasible (Illinois Department of Transportation 2010 and Oregon Department of Transportation 2014). Other factors for prioritization include structural vulnerability, anticipated failure modes, and structure use (Olsen et al. 2016 and Landry 2018). More details are shown in Table 2-8.

Table 2-8. Considerations for Structure Prioritization (Olsen et al. 2016)

Feature	Consideration
Initial information	Initial reports from Fast Reconnaissance including the media or the general public will help narrow down where damage is most intense and which structures have experienced major damage or collapse.

Feature	Consideration
Structural Vulnerability	This includes the year the structure was built and design criteria. Structural characteristics that increase the likelihood of failure from an earthquake (and other hazards) include superstructure discontinuities (simply supported spans instead of a superstructure with continuity), skew angle, bearing type and height, lack of lateral bracing, deteriorated condition (as reflected in the condition ratings especially the primary and secondary structural members), seat length and width, lack of restraint from lateral displacement, vulnerable structure type (e.g., trusses), redundancy, poor seismic detailing of concrete reinforcement, etc.
Anticipated mode of failure	In planning analyses, one can identify likely modes of failure for critical structures and assess their impacts to determine how catastrophic the failure of that structure would be.
Geological conditions	Structures close to rivers and in other areas with granular soil and high water tables can be damaged from liquefaction including settlements and lateral spreading. Structures close to unstable slopes or near active landslides should also be given high priority. In the case of flooding, sites with expansive or collapsible soils can also lead to higher levels of damage.
Condition	Any structure will deteriorate with time due to exposure to elements and fatigue from repeat loading, degrading structural capacity. Structures that are operating well beyond their design life could also be more vulnerable. However, repairs and modifications could also have been made. Note that these ratings and databases can often change regularly since deficient structures will likely be placed in high priority for repairs. The Recording and Coding Guide for Bridges denotes fields 58–60 as condition ratings for deck, superstructure, and substructure, respectively.
Elements	In addition to the overall structure condition, some elements may be in poor condition and could be the weak link with the additional loading from an emergency event.
Traffic levels	Structures with higher traffic levels normally should be given higher priority. The traffic level can be measured by the annual average daily traffic. Highways with links to critical infrastructure (hospitals, fire stations, etc.) should be given higher priority.
Detour availability and impacts of road closures	How does this structure fit in with the network? Structures on routes with few or long detour options available should be given higher priority.
Structure use	In addition to carrying traffic loads, some structures will also support vital utilities such as power lines and pipelines. These structures should be given higher priority. Additionally, some structures may be important for utility access.
Construction Projects	Both current and near-future construction projects should be considered in the prioritization since they will affect the traffic network.

Structure prioritization approaches often depend on the type of extreme event. For earthquakes, prioritization is frequently adjusted by earthquake magnitude and corresponding distance away from the seismic epicenter (Montana Department of Transportation 2022, Illinois Department of Transportation 2010, Oregon Department of Transportation 2014, and Oklahoma Department of Transportation 2016). Seismic fragility curves can be developed for different levels of ground motions to predict damage levels and to inform resource allocation decision (Choi et al. 2004). Mapping technologies like HAZUS-MH and REDARS modeling are used to identify earthquake magnitude and anticipated damages (Marsh & Stringer 2013).

For tsunamis, fragility curves can be used to determine expected damages based on inundation depth of historical data (Koshimura et al. 2009). Hurricane and Storm Surge damage can be predicted from height of floods and hurricane category or wind speed (Olsen et al. 2016). Floods are based on the warnings issued by the National Weather Service or the bridge's risk to scour (Pennsylvania Department of Transportation n.d., Iowa Department of Transportation 2010). For collisions, fires, and man-made events, the number of impacted structures influence prioritization if such needs are warranted (Olsen et al. 2016).

The questionnaire indicated that half of respondents had documented procedures for structure prioritization (see Appendix Table B-2). However, 60% of respondents indicated they were "well-prepared" in their ability to prioritize inspections (see appendix Figure B-16). This suggests that state DOTs' procedures are not necessarily documented but agencies feel prepared based on their prior experiences.

2.3.3 Implementation

Emergency assessment consists of two parts: inspection and evaluation. Both are critical to determine the extent of damage and the next steps to restore service. Emergency inspection methods are similar to routine inspection methods, as described by the MBE, but differ on the speed at which information is collected and the approach to prioritization. Typical evaluation procedures abide by normal procedures outlined in the MBE, including load rating and laboratory testing.

2.3.3.1 Emergency Inspection

Emergency inspection techniques heavily reply on visual inspection. Depending on the level of inspection (first look or detailed assessment), additional inspection technologies such as non-destructive testing and evaluation (NDT&E) may be required. For any inspection level, inspectors assess main bridge superstructure and substructure elements as well as the deck and approaches (Figure 2-4).

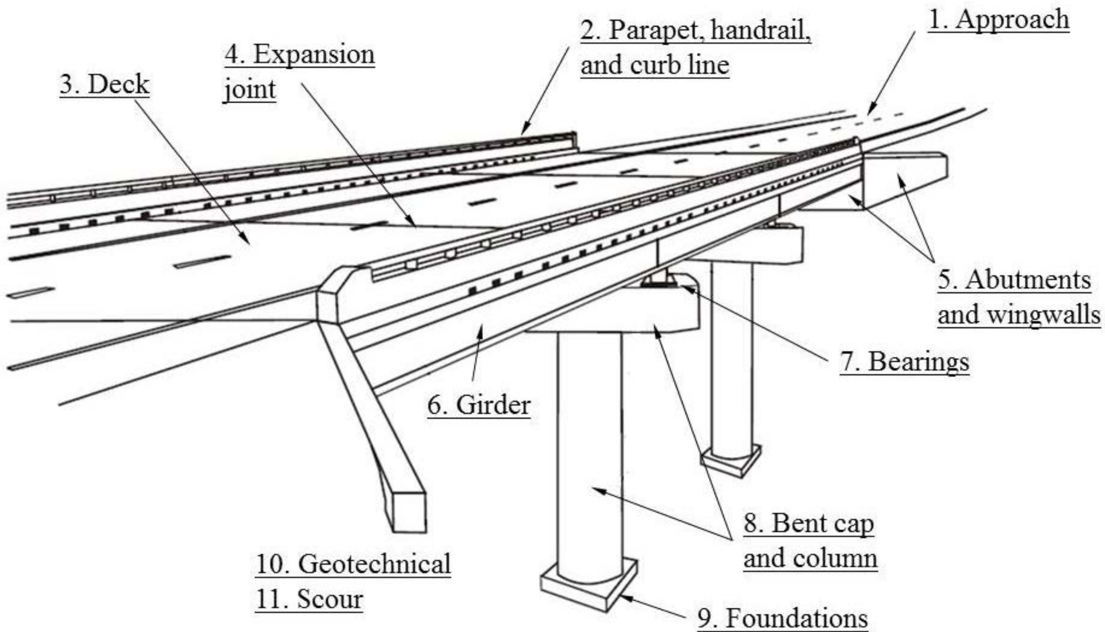


Figure 2-4. 11 Point Inspection Procedure (Olsen et al. 2016)

NCHRP Research Report 833 presents a four stage assessment process for emergency events (Figure 2-5). The four stages are: Fast Reconnaissance (FR), Preliminary Damage Assessment (PDA), Detailed Damage Assessment (DDA), and Extended Investigation (EI). Each level of assessment builds on information collected in the previous assessment. If a structure is deemed as “unsafe”, then further investigation is required.

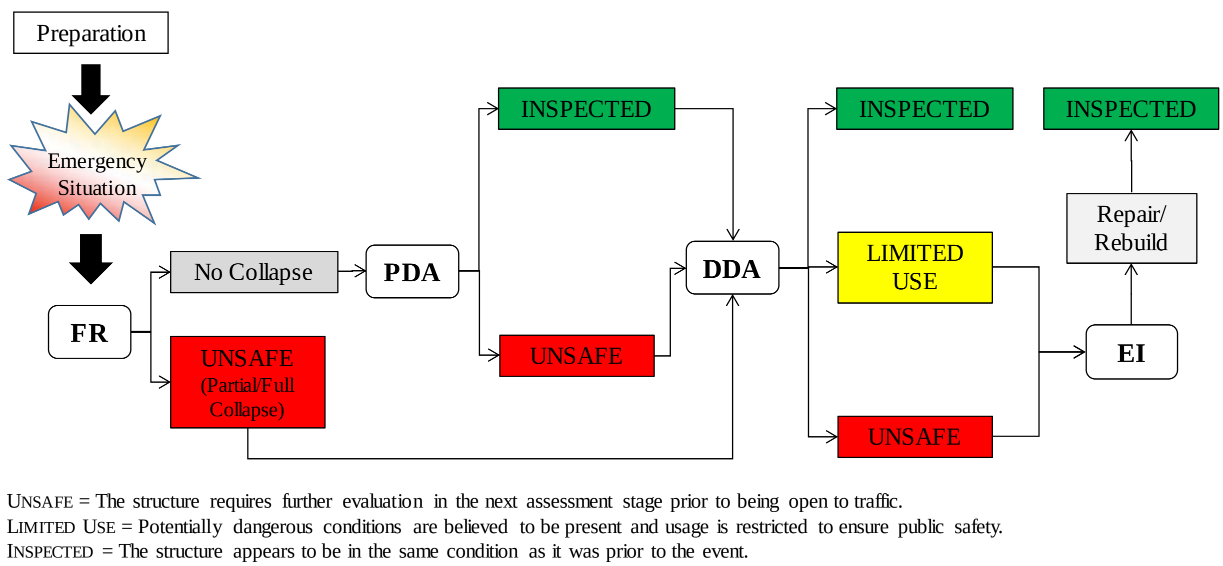


Figure 2-5. Assessment Stages and Subsequent Primary Level of Coding (Olsen et al. 2016)

2.3.3.2 Emergency Evaluation

Like routine inspections, emergency inspections categorize damage based on level of damage (Harries et al. 2009). The specific metrics vary by each damage state, but generally follow a none-minor-moderate-severe approach. Concrete bridges will have different types of visible damage than steel structures, so it can be difficult to compare the severity and repair options between structures of different material types. However, by comparing damage states, it can make it easier for state DOTs to decide how to allocate resource for repairs, especially for widespread events such as earthquakes, hurricanes, or floods. Some state DOTs have more refined methods for emergency evaluation based on event type, using flowcharts (Veletzos et al. 2008).

2.3.4 Technology

State DOTs use a variety of technologies to assist with structural assessments. Remote sensing techniques such as lidar, UAS, and GIS are often used to complete inspections or organize findings (Chen n.d., Gusella et al. 2007, and ESRI 2016). Apps such as FHWA’s Mobile Solution for Assessment and Reporting (MSAR) and instruments for data collection (wind and rain gages, seismic motion collection, and long-term monitoring) aid in the inspection process (FHWA n.d., Cooper et al. 1994, Hawrylak & Mickle 2009, Dimaculangan et al. 2010, Jalinoos et al. 2019, Spencer et al. 2019 and Sun et al. 2020).

2.4 Rapid Restoration

Rapid restoration of service is an important component of the recovery phase of an extreme event and is ultimately the backbone for community resilience and enables distribution of supplies and restores economic activity. Rapid restoration of service to a bridge includes several steps: the decision to repair or replace the structure, the design selection, the bidding and contracting process, and the construction. With each of these steps, there is an option to follow traditional engineering practices, or to apply emerging technologies to speed up the process. Factors such as time, money, resources, and safety govern these decisions. Overall, the quest for rapid restoration of service has led to a variety of innovations in recent years and has propelled the bridge industry into new levels of efficiency.

2.4.1 Bidding & Contracting

State DOTs often have bidding and contracting procedures that they use regularly. Each procedure leads to its own rules and regulations to ensure a fair and effective process. To stay organized, some states developed flowcharts to efficiently consider all aspects of the project (HDR 2014). Other states established emergency bridge contracts that allows the DOT to hire consultants/contractors to repair or replace structures in the event of an emergency. These emergency contracts, however, can only be activated with the approval of the Chief Engineer. Contractors are arranged as needed, and payments are made on a force account method. Due to the omittance of typical (i.e., non-emergency) contracting techniques and bidding processes, this contracting method tends to cost more, and is only considered in extreme cases. As part of the contract and the need for a rapid repair, some states store temporary structures that can be deployed to repair some level of service while a permanent repair is under development (Marchione 2014).

NCHRP Report 753 provides a guide for pre-event recovery planning and recommends state DOTs consider a variety of options when it comes to bidding and contracting (Bye et al. 2013). Using a list of pre-qualified contractors can speed up the contracting process. Some examples of pre-qualified contracting include the options listed in Table 2-9.

Table 2-9. Pre-Qualified Contracting Options (Bye et al. 2013)

Contract Option	Conditions of Use
Pre-Event Contracts	If normal federal-aid requirements are met, including competitive low-bid advertisements, pre-event contracts are allowable. FHWA has approved boilerplate language for Construction Engineering and Assessment (CEI) services, debris monitoring, cut and toss and debris removal, traffic control signals, permanent lighting, and signal repair. Pre-event contracts for other work types may be acceptable as long as FHWA federal-aid requirements are met. For pre-event contracts that identify a sole source material supplier or proprietary product, a Public Interest Finding must be sent to FHWA for approval in advance of executing the contract, as per 23 CFR 635.411.
Pre-Existing Contracts	Existing contracts may be used to provide for emergency services and the purchase of commodities if the emergency service or commodity required falls within the original intent of the contract, or if the scope of services/specifications addressees, providing for emergency situations.
Stand-by Contracts	Stand-by contracts can be put in place for critical recovery equipment and supplies to help ensure that recovery supplies are available in the quantities needed and at a reasonable price. Typically, these contracts establish prices as those in effect on the day before the event occurred.

Table 2-10 outlines popular rapid restoration contracting types. These methods are frequently employed across the nation for rapid bridge and culver restoration. These procedures should maintain a competitive bid process to ensure the fairest possible methods given the circumstances. In most instances, forgoing traditional methods are acceptable if there is a threat to the public, or emergency personnel is unable to effectively work due to limited or eliminated access (Alaska Department of Transportation and Public Facilities 2018). An emerging contracting type, flash tracking, has been developed out of recent research projects. It integrates engineering procurement and construction (EPC) to create a time-driven project. Flash tracking helps reduce communication barriers during each of these processes to lead to shorter project durations. This method also centers on the early engagement of key stakeholders and clearer lines of communication between parties (Austin 2016).

Table 2-10. Popular Rapid Restoration Contracting Types and Provisions

Contracting Type/Provisions	Description	Strengths	Weaknesses
Best Value	• Contractor(s) selected based on best price and best qualifications, thus creating a "best value" • The "best" can be determined based on a point system where contractors can score more points based on their technical expertise and cost	• Most qualified contractor selected • Pairs well with ABC projects	• Requires contractors to maintain a special list of qualifications • Low bid contractors may not always qualify
Design-Build (New York State Department of Transportation 2011)	• Construction and design occur concurrently	• Reduces time required for final deliverables • Thrive in situations where engineers have flexibility with design – leads to more innovations and creativity	• May require legislative action or DOT leadership approval • May reduce competition as not all companies can put together an effective team • Contract management is more challenging.
A+B Bidding (Culmo 2011, WSDOT 2016)	• A+B Bidding works by looking at the cost (A) and the time (B) when making a contractor decision • This contracting method was used after the Skagit River Bridge Collapse in Washington. Washington DOT used this process paired with early milestone completion incentives, which helped to expedite the repair process	• Can reduce project time by considering time and cost • More holistic contracting approach	• Requires additional expertise to prepare contract clauses and oversight during construction

Contracting Type/Provisions	Description	Strengths	Weaknesses
A+B+C Bidding	• Adds a milestone (C) component to A+B Bidding • User costs are factored into the C component, which often includes incentives or disincentive if the project milestones are or are not met on time • The dollar value of these incentives/disincentives are based on these user costs to incentivize a quicker completion date	• Quicker completion date • Consider the costs associated with delays and closures for motorists during construction	• Requires additional expertise to prepare contract clauses and oversight during construction
Incentives and Disincentives (I/D Clause) (Culmo 2011)	• Can be added to penalize the contractor or provide financial incentives to complete and meet set project milestones • Incentive and disincentive amounts are usually the same o If not, recommended the incentive is less than the disincentive. o Actual amounts can be determined by the road user costs	• Provides contractors with motivation to meet project milestones • Rewards accelerated performance	• Contractor may cut corners to reduce the likelihood of a financial loss • Contractor may view delays as a punishment • May exclude smaller contractors with limited resources

2.4.2 Implementation

To select a restoration solution, state DOTs use a variety of tools including tables, charts, and flowcharts. Cost-benefit analyses are often paired with these tools to help select a repair solution (SDOT Blog 2020). Other key considerations include safety, bridge type, standards, damage levels, traffic control, cost, and features crossed (New York State Department of Transportation 2019).

Restoration methods vary greatly on bridge type and the level of damage. For most restoration options, state DOTs have the option to consider accelerated bridge construction (ABC), which uses prefabricated components to quickly assemble structures in less time and decrease service interruption to the public (Culmo 2011, Sivakumar 2017). Standardized plans can also expedite design and construction (Malik et al. 2002, Nebraska Department of Roads Bridge Division 2016, and Sivakumar 2017).

2.4.2.3 Temporary Solutions

Some situations may require the implementation of temporary repairs. Temporary repair solutions are often used for a variety of reasons, such as: the need for a quick reopening of a heavily damaged system; lengthy repair times due to long-lead items or delays in materials, equipment, or personnel; environmental factors like weather conditions; and funding limitation. Temporary repairs details vary depending on the type of extreme event, but there are some solutions that are applicable to many situations.

Modular bridge systems or portable panel bridges (such as a Bailey Bridges) are systems that state DOTs can have on hand to quickly deploy in times of need (HDR 2014, Washington State Department of

Transportation 2014). Temporary shoring can also harness the remaining capacity of the damaged structure until permanent solutions can be implemented (Nebraska Department of Roads Bridge Division 2016).

Questionnaire respondents indicated that "procurement of materials" was their biggest impediment to rapid restoration, following by "contracting qualified contractors" (Table 2-11). Temporary solutions are a valuable option to state DOTs while obstacles like procurement and securing qualified contractors can are being resolved for permanent repair solutions.

Table 2-11. Impediments to Rapid Restoration. N=38 DOTs.

Ranking*	Response	Avg Ranking	Max	Min	Median	Standard Deviation
1	Procurement of materials	1.9	1	7	1	1.32
2	Contracting qualified contractors	2.9	1	6	3	1.56
3	Lack of technical expertise	3.2	1	5	3	1.39
4	Lack of guidelines	3.8	2	5	4	0.93
5	Lack of training	3.9	1	6	4	1.47
6	Other	5.4	1	6	6	1.55

* 1 is the biggest obstacle and 6 is the least obstacle

2.4.2.4 Permanent Solutions

State DOTs use a variety of repairs for permanent solutions to bridge damage. The repair solutions vary depending on the bridge element, material, and defect type. A detailed list of possible solution with references is included in Appendix F of *NCHRP Research Report 1098*.

2.4.3 Technology and Advanced Materials

There are many design aids and software are on the market that help state DOTs design or select restoration options (Short Span Steel Bridge Alliance 2020). 3D modeling from photogrammetry or lidar can generate models of the structure and ensure proper alignment of repair components and simulate assemblies and construction sequencing (Hannon 2007 and Brenner et al. 2020).

Construction progress monitoring techniques such as strain gauges and time-lapse videos help ensure high-quality final products and assist with cost estimation (Hannon 2007, Watts 2013, and Alipour 2016).

In addition to progress tracking, state DOTs use advanced materials such as fiber reinforced polymer (FRP), ultra-high-performance concrete (UHPC), and titanium reinforcement bars as repair solutions (Harries et al. 2009, O'Connor 2010, Brown 2011, and Vavra 2016).

2.5 Case Studies

Twenty-seven Case Studies (Table 2-12 and Appendix C) were document in NCHRP 14-45 to better understand the current procedures and techniques used by DOTs and consultants for emergency planning, assessment, and rapid restoration of service for bridges during recent extreme events. These brief case studies include a diverse set of hazards as well as type of responding agency to present the full landscape of current practices. These cases studies generally focus on extreme events within the past decade to ensure recent practices are described. However, a few landmark events from the mid-1990s are also included to ensure lessons learned from historic events are maintained. Each case study is brief, typically 3-5 pages in length, and includes a number of photos to illustrate the techniques used. A common format and structure were adopted for easy sharing and inclusion within BARRT, the guide implementation tool. This common structure also allows state DOTs to develop their own case studies from recent extreme events which can be easily shared both within the agency and with outside agencies such that this can be a living database.

Table 2-12. List of Case Studies

Case Study Number	Case Study Name	Hazard
1	Denali Earthquake	Earthquake
2	Japan Earthquake & Tsunami	Earthquake/Tsunami
3	Nisqually Earthquake	Earthquake
4	Northridge Earthquake	Earthquake
5	Arkansas Flood	Floods
6	Michigan Flood	Floods
7	Hurricane Harvey	Hurricane
8	Hurricane Katrina	Hurricane
9	Chester Creek I-95	Fire
10	Iowa Perry Creek	Fire
11	Alaska Collision	Collision
12	Arkansas I-555 and Highway 1B	Collision
13	Arkansas River Bridge	Collision
14	Mathews Bridge	Collision
15	San Jacinto River I-10	Collision
16	Scottsburg Bridge	Collision
17	Skagit River Bridge	Collision
18	Pennsylvania Department of Transportation Public-Private-Partnership	Procurement
19	Mississippi River Bridge I-35W	Man-Made
20	Sava River Bridge at Brcko	Man-Made
21	West Seattle Bridge	Immediate Action Inspection
22	Franklin Ave	Other
23	I-84 Bridges	Other
24	Keg Creek	Other
25	Salt Lake City Olympics	Other
26	State Route 30 & Bessemer Ave	Other
27	Washington ABC	Other

2.6 Conclusion

For emergency planning, state DOTs have developed a series of procedures and policies to prepare their states for extreme events. State DOTs generally have plans to establish a command center that is in a well-known, easily accessible location. In the event of a widespread incident, such as a hurricane or earthquake, there may be multiple command centers for each impacted region. These command centers oversee delegation of responsibilities to assessment teams and facilitate communication within and across agencies. Many state DOTs are aware of funding sources, including federal aid packages, state relief funds, or local bonds and how to collect information from crowdsourcing through social media. Mobile phones, landlines, radio, and in-person meetings are the main channels of communication during and after an emergency event.

To reduce the likelihood of severe damage after an emergency event, there are a variety of retrofits state DOTs can implement, many of which are event specific. These retrofits are preventive measures that can improve baseline conditions, which significantly improves the structure's response to storm loads and other impacts. Plans for detours in the event of road or bridge closures, evacuation routes, and other route alterations should also be considered in the planning phase. New and emerging technologies such as apps and mapping devices can help prioritize preparation efforts and identify topics for improvement in response plans.

During the last phase of an emergency event, bidding and contracting is an important step to partial or full restoration. There are many possible repair solutions. These depend on many site-specific factors such as location, impact to traffic, and availability of personnel. Once a contracting type is selected, material procurement may include purchasing of new materials, or using stockpiled resources. Prefabricated components help expedite the restoration process, and usually consist of precast concrete or steel components. Prefabrication elements pair perfectly with ABC, a process that increases worker safety, reduces the impact on traffic, and shortens project duration by manufacturing most of the structure offsite, or in an adjacent work bed. Then, sections of the structure are lifted, launched, or jacked into place. Once the finishing touches are completed, the structure can be reopened to traffic.

Temporary repair solutions are often implemented to restore some service to damaged bridges while permanent repair solutions are being designed. Examples of common temporary solution include modular bridges, temporary shoring of damaged elements and partial lane reductions.

Emerging technologies and advanced materials such as construction monitoring, Ultra High-Performance Concrete joints and FRP, can improve the quality of restores solutions and help prepare for the next emergency event.

Twenty-seven Case Studies are documented in this research overview document to better understand the current procedures and techniques used by DOTs and consultants for emergency planning, assessment, and rapid restoration of service for bridges during recent extreme events. These brief case studies include a diverse set of hazards as well as type of responding agency to present to allow the reader to obtain an overview of recent and current practices.

Chapter 3: Evaluation of Rapid Restoration Procedures

The objective of this chapter is to identify the procedures for response planning, assessment, and rapid restoration from the literature review, evaluate these procedures, and generate a list of recommendations to serve as the basis for the guide and corresponding implementation tool. This chapter is organized into the following sections:

- Evaluation – This section summarizes the process the project team followed to analyze the procedures identified in the literature review and questionnaire.
- Gaps - From the identified procedures, missing elements and procedures were determined. These consist of procedures that were either missing altogether or not fully developed.
- Recommendations – The recommendations based on the previous sections were used as the basis for the guide and implementation tool.

3.1 Evaluation

The project team collected and reviewed relevant literature, research findings and information related to the response planning, emergency assessment, and rapid restoration of service of bridges and culverts in extreme events. As part of the process of reviewing existing literature, the project team evaluated and identified common and promising procedures, which are broad ranging along the event timeline and vary across agencies. A total of forty-seven procedures were deemed viable options based on our collective expertise and experience. These procedures include 19 for planning, 11 for emergency assessment, and 19 for restoration. These procedures were identified and evaluated based on several important factors including:

- ***Personnel requirements and qualifications*** – The personnel at transportation agencies have diverse skillsets. The recommended procedures must leverage the existing skillset of personnel and require minimal specialized training. Additionally, the organizational structure and chain of command must be clear such that everyone understands their role and can appropriately execute their responsibilities.
- ***Communication*** – Effective communication is critical for an efficient extreme event response. Communication channels must be available between the command center and field personnel, between field personnel, and between agencies. Managers in the command center require accurate real-time field data to make appropriate decisions. The procedure must allow for multiple secure communication channels to ensure the free flow of accurate information.
- ***Data collection*** – Field data (e.g., damage assessments of bridges and culvert and personnel status updates) must be collected and processed rapidly in a geospatial format that facilitates sharing with all appropriate personnel. Ideally, real-time field data is available to all field personnel and managers so that all employees have the same picture of the events on the ground. Real-time situational awareness is only possible if sufficient communication systems are available (e.g., internet access and cellular network). This level of connectivity may not be available to all field personnel, so the procedure must allow for alternative data collection methods.
- ***Levels of damage assessment*** – The procedures must include multiple levels of damage assessment to maximize the skillset of existing field personnel and facilitate an efficient response. Rapid

assessments are critical to the efficient response in large-scale events and help managers to understand the geographic extents of the event and to prioritize response efforts. Detailed assessment approaches are necessary to ensure public safety following an event.

- ***Effectiveness of approaches for restoring service*** – The existing procedures have a range of application. Some procedures focus on individual phases of the extreme event timeline (i.e., response planning, assessment, or rapid restoration), while other procedures are applicable to multiple phases. Regardless of the specific focus, the procedure must improve the effectiveness of the overall response and restore service to the general public rapidly and cost effectively.
- ***Common and emerging damage detection techniques*** –The project team recognizes that visual inspection is the most common post-extreme event bridge damage detection technique, followed by hand-held non-destructive testing and evaluation techniques and sonar surveys (Alipour 2016). Many DOTs have adopted unmanned aircraft systems (Gillins et al. 2018) to make inspection processes more efficient, and successful programs are recommended (Banks et al. 2018). The recommended procedures must leverage these existing approaches to be immediately useful and, at the same time, must be flexible enough to accommodate other potential emerging techniques to ensure the procedures remain useful and relevant for many decades.
- ***Range of application*** - The most frequent causes of bridge failures in the United States are due to collisions from over height vehicles and from hydraulic sources such as scour, flood, and debris flow (Alipour 2016). Vehicle collisions can cause extreme failure; yet they are highly localized events and can be managed by local and/or state personnel. Hydraulic events can cause damage to multiple bridges over a large region and may require a response from multiple states. In addition, from recent Midwest flooding events, it is observed that such regional flooding can sustain for weeks to months. The recommended procedures should be applicable to these more common extreme events and should also be applicable to the rare but larger events such as earthquakes and hurricanes. Use of the procedures on these common events will serve as training of personnel and will facilitate resilience and the rapid restoration of service in the most complex extreme events.

The project team systematically identified the strengths and weaknesses of each existing procedure that was considered a viable option. The collective experience of the team was used to perform this task. These existing procedures are grouped based on the most relevant response phase (i.e., planning, emergency assessment, and rapid restoration). Table 3-1 lists the procedures evaluated. The descriptions and identified strengths and weaknesses of each procedure are included in Table 3-2, Table 3-3 and Table 3-4.

Table 3-1 List of Evaluated Procedures

Planning Phase	Emergency Assessment Phase	Rapid Restoration Phase
General Emergency Response • Command Center • Incident Management Protocols (NIMS/TIM) • Partnerships / Contacts with Key stakeholders • Emergency Operation / Response Plan • Internal and External Communication Plan • Emergency Funding Readiness **Resource** • Emergency On-Call (Stand-by) Contracts • Staging / Stockpiling / Asset Positioning Plans • Training & Exercises • Baseline Condition • Bridge Monitoring Systems • Preventative Measures/Maintenance **Prioritization** • Hazard Characterization and Modeling Tools • Assessment Prioritization Plan **Defined Assessment Protocols** • Response Levels & Scalability of Plans • Closure Plans and Protocols in Place • Assessment Reporting & Data Collection Processes in Place	**Information Management** • Crowdsourcing • Alert Systems / Push Notifications • Damage Assessment and Data Collection • Data Infrastructure and Asset Management • Engineering Needs Assessment **Assessment Protocols / Process** • Multi-Level Assessment Process • Refresher Training **Field Assessment Technologies** • Structural Assessment • Non-destructive Testing • Structural Health Monitoring (SHM) Check • Specialized Technology Based Assessment	**Logistics** • Stakeholder Engagement • Emergency Declaration • Expedited Approval Processes • Lessons Learned Documentation **Contracting** • Pre-Qualified Contracting • Emergency Contracts • Accelerated Project Delivery Contracting / Innovative Contracting • Public-Private Partnerships • Fast Track Contracting Provisions **Restoration and Repair Techniques** • Temporary Supports and Structures • Modular Bridge Systems • Prefabricated Components and Systems • Rapid Structural Placement Methods • Repair/Replace Decision-making guidelines • Recommended repair/restoration chart • Design Process • Standard Repair Design Documents • Laser Scanning • Structural Monitoring

Table 3-2 Evaluation of Planning Phase Procedures

Planning Phase Procedure		**Description**	**Strengths**	**Weaknesses**	**Case Study**	**Questionnaire**
General Emergency Response	Command Center	Provides incident leadership, a central location for situational awareness, communication and overall response decision making	Common practice. Improves communication and coordination with senior management, politicians, the press, and the public. Applicable to a wide range of events. Improves overall response efficiency	None identified	15, 19	-
	Incident Management Protocols (NIMS/TIM)	Protocols providing a framework for what to do in both small and large incidents, including a description of the chain of command to define lines of communication	Common practice. Applicable to all types of extreme events	None identified	-	-
	Partnerships / Contacts with key stakeholders	A known list of contacts to assists with flow of communication. Role and responsibility of partners and stakeholders are defined to ensure relevant information is shared efficiently	Improves response communication and coordination. Applicable to all types of extreme events	Requires regular pre-event planning and communication	25	-
	Emergency Operations / Response Plan	A document that describes how an agency will respond to and recover from an emergency. These can include direction on traffic regulations during an emergency event	Common practice	May be general and typically limited to a single event type.	1	-

Planning Phase Procedure		Description	Strengths	Weaknesses	Case Study	Questionnaire
General Emergency Response	Internal and External Communication Plan	Internal: phone, radio, email, IM, text, etc. External: 511, reverse 911, DOT website, social media, news (via Public Information Officer)	Common practice. Utilizes multiple secure communication channels to ensure free flow of accurate information	May require training	21	-
	Emergency Funding Readiness	A list of information and documents needed to apply for emergency funding from various agencies.	Helps secure funding rapidly to improve response effectiveness. Ensure the needed information is collected during the event to secure funding. Applicable to all types of extreme events	Requires regular pre-event planning as forms can change over time. The requirements vary between funding agency and may change over time	-	Q1, Q4
Resources	Emergency On-call (Stand-by) Contracts	Contracts between agencies and experienced consultants and contractors. These contracts, also known as Stand-by contracts, are in place prior to an extreme event	Qualified personnel are available when needed. Eliminates time consuming bidding process during or immediately following an extreme event. Maintains a competitive bidding process. Applicable to all types of extreme events	Requires upfront costs. May require continuous funding.	4	Q1, Q7

Planning Phase Procedure		Description	Strengths	Weaknesses	Case Study	Questionnaire
Resources	Staging/ Stockpiling/ Asset Positioning Plans	Plans that describe and define that strategic placement of important assets (materials, equipment, and personnel) for rapid access and use	Ensures materials, equipment and personnel are available	Requires pre-planning and communication. Most effective for extreme events that provide sufficient advanced warning such as hurricanes or floods	-	Q1, Q5
	Training & Exercises	In-person training, webinars, drills, and mock scenarios. These can encompass a variety of scopes and levels including national (i.e., NIMS, NRF), state/region (i.e., TIMs, Emergency Response Plans), specific/local (i.e., assessment, communication)	Common practice	Requires upfront cost	-	Q4
	Baseline Condition	Defining the pre-event condition of the bridge network. This can include providing emergency assessment teams access to routine inspection reports/original design documents (as-built drawings/calculations). In addition, the baseline condition can be incorporated into the agency's asset management system	Improves event response efficiency and assessment accuracy	Requires planning and mechanism to easily access relevant information during an event	9	-
	Bridge Monitoring systems	Utilize systems that can monitor the status of a bridge. These can include structural health monitoring (SHM) and flood monitoring. Scour monitoring is critical for flooding events	These systems can inform agencies of damage to existing structure from a variety of events (mostly likely earthquake, flooding events, and collision)	Requires upfront costs and may require continuous funding. SHM is typically only utilized on a select few long-span critical bridges and does not provide information on the full highway network	-	-

Planning Phase Procedure		**Description**	**Strengths**	**Weaknesses**	**Case Study**	**Questionnaire**
Resources	Preventative Measures/ Maintenance	Actions that can be taken prior to the event to minimize the impact on the community. They vary in scope and can differ for event types. Can include full replacement of highly vulnerable bridges, extensive retrofit of full bridge or local components of bridge, installing debris deflectors/ catchers and scour countermeasures. Protective devices for collision and fire such as closed-circuit monitoring and impact barrier protection	Improves community resilience. Can reduce or eliminate completely the level of damage experienced	Requires upfront cost and pre-event planning. It is unlikely that one preventative measure is applicable to all extreme event types	-	-
Prioritization	Hazard Character-ization and Modeling tools	Computer-based tools that allow the user to create interactive queries, store and edit spatial and non-spatial data, analyze spatial information output, and visually share the results of these operations by presenting them as maps. Can be used for both internal and external communication and to communicate information to the general public. These tools are often used to characterize the hazard and identify at-risk bridges. (e.g., GIS, crowdsourcing, HAZUS, FEMA flood maps, USGS ShakeMaps / ShakeCast, Hurrevac)	Common practice. Applicable to all event types. Improves response efficiency and decision making. Improves communication on many levels (intra/interagency, and to public). Can allow for real-time field date to be available to all field personnel	Requires planning and training. May require continuous funding for software licensing	6, 8	Q1, Q9

Planning Phase Procedure		**Description**	**Strengths**	**Weaknesses**	**Case Study**	**Questionnaire**
Prioritization	Assessment Prioritization Plan	Develop a plan that defines the order in which bridges should be assessed. Often includes a vulnerable structures list, priority lists and priority routes. Can also include an ownership plan that assigns all critical structures to local maintenance personnel year round as well as plans for accessing the structures during an emergency	Improves response efficiency and community resilience	Requires planning and knowledge of baseline condition of bridge network	-	Q6, Q7
Defined Assessment Protocols	Response Levels and Scalability of Plan	Assist with asset management and communication, particularly for events that have little or no warning and can have a large geographic footprint	Leverages the existing skillset of personnel. Requires minimum specialized training. Improves communication and response efficiency. Applicable to a broad range of events	Requires planning and training	-	-
	Closure Plans and Protocols in Place	Pre-established procedures for ordering emergency closures, and for preventing travel, and pre-established detours if critical structures are closed	Common practice. Applicable to all events	Requires planning and training	-	-
	Assessment, Reporting & Data Collection Processes in Place	Systems that are in place to allow fast assessment of damages, and to report the damages. Technology based techniques are available.	Improves communication and response efficiency	Requires planning and training. Field inspection teams must be identified and trained.	-	-

Table 3-3 Evaluation of Assessment Phase Procedures

Assessment Phase Procedure		Description	Strengths	Weaknesses	Case Study	Questionnaire
Information Management	Crowdsourcing	The practice of obtaining information by enlisting the services of a large number of people, typically via the internet or through social media platforms. This is increasingly a way for agencies to assess the scope of an extreme event and is typically part of the Fast Reconnaissance assessment level	Rapid approach to assess the scope of an event. Improves communication and situational awareness	Requires training	13	Q18
	Alert Systems / Push Notifications	Notification systems to inform agencies, personnel, and the public of critical information. For example, the 511 system and the Flash Alert system from the Oregon Office of Emergency Management which has been used to notify the DOT and the public about bridge collisions	Common practice. Improves communication and coordination. Applicable to a wide range of events. Improves overall response efficiency	Requires training	16, 21	-
	Damage Assessment and Data Collection	The process of collecting and reporting the result of each assessment stage to the command center	Improves response communication and coordination. Applicable to all types of extreme events. Improves situational awareness and event response efficiency	Process and forms vary across agencies within a state and across states	-	-

<u>Assessment</u> Phase Procedure		**Description**	**Strengths**	**Weaknesses**	**Case Study**	**Questionnaire**
Information Management	Data Infrastructure and Asset Management	Systems that collect and process the assessment data from the various inspection levels to provide situational awareness. These systems can help managers determine the best course of action. Typically include GIS and structural inventory databases	Applicable to all event types. Improves communication on many levels (intra/interagency, and to public). Leverages common/existing techniques and can accommodate other potential emerging techniques. Improves response efficiency and decision making. Can allow for real-time field date to be available to all field personnel	Requires continuous funding for maintenance and training	6, 8	-
	Engineering Needs Assessment	Engineering needs are assessed, and decisions are made on how those needs will be met to facilitate the rapid repair(s); e.g., in-house, outside consultant, included in design-build, etc.	Common practice. Applicable to all event types	Requires trained personnel	-	-
Assessment Protocols/Process	Multi-Level Assessment Process	A hierarchy of levels can improve situational awareness to assist with event planning and efficient utilization of assets. The number and names of these assessment levels vary (initial, Level I, II, III or FR, PDA, DDA EI) but process and objectives are similar	Leverages the existing skillset of personnel. Improves communication and response efficiency. Applicable to a broad range of events	Requires planning and training	-	-

Assessment Phase Procedure		**Description**	**Strengths**	**Weaknesses**	**Case Study**	**Questionnaire**
Assessment Protocols/Process	Refresher Training	Training that occurs during or just prior to an event. Often for personnel who are called into action but may not perform assessments on a regular basis (e.g., design engineers who are typically in the office).	Leverages skillset of existing personnel	Requires planning and training	-	-
Field Assessment Technologies	Structural Assessment	An important and necessary step in the restoration process, where inspection teams are deployed and equipped to report findings. Typically performed with visual inspection and simple hand tools as part of a Preliminary Damage Assessment or Detailed Damage Assessment levels.	Common practice. Does not require specialized training or personnel. Applicable to all events	Requires trained personnel. Assess one bridge at a time	2, 6, 16, 20, 22	Q5, Q16
	Non-destructive Testing	Testing methods that do not damage the structure. Typical methods include magnetic particle testing, ground penetrating radar, ultrasonic testing, and impact-echo. These methods are typically part of the Detailed Damage Assessment level.	Common for detailed damage assessments. Applicable to all events	May require specialized equipment and/or trained personnel	16, 21	Q16

Assessment Phase Procedure		Description	Strengths	Weaknesses	Case Study	Questionnaire
Field Assessment Technologies	Structural Health Monitoring (SHM) Check	A damage detection or characterization strategy for real-time assessment of structural condition. A typical system includes a sensor network, a data processing system, and a health evaluation system. During the assessment phase existing SHM systems are checked to see if any limit states have been exceeded. This can be part of the Fast Reconnaissance or Preliminary Damage Assessment levels	Rapid and accurate assessment. Improves response efficiency	Require specialized equipment and trained personnel	14, 19, 21	-
Field Assessment Technologies	Specialized Technology Based Assessment	Inspecting or assessing a bridge using more advanced technology. Examples include lidar, photogrammetry, UASs, Satellite Imagery, sonar. These methods can be part of the Detailed Damage Assessment or Extended Investigation assessment level	Rapid assessment rate. Applicable to all events	Require specialized training and equipment	6, 15, 16, 26	Q5

Table 3-4 Evaluation Rapid Restoration Phase Procedures

Rapid Restoration Phase Procedure		Description	Strengths	Weaknesses	Case Study	Questionnaire
Logistics	Stakeholder Engagement	All key personnel identified during the planning phase need to be alerted as soon as possible of the emergency event and aware of their roles to provide input to the decision makers	Can improve long-term restoration efficiency and improve construction quality	Requires planning and time. Must regularly revisit relationships as personnel change with time	13, 19, 21, 25	-
	Emergency Declaration	A formal declaration that opens additional funding possibilities. Depending on the state this may also allow for expedited approval processes. Executive Orders may allow for certain regulations to be suspended (e.g., procurement, environmental)	Can improve restoration efficiency by suspending procurement regulations	May suspend environmental regulations	6, 9, 14	-
	Expedited Approval Processes	Procedures that allow for rapid approval during an extreme event. These often follow the normal day-to-day process but have higher priority to reduce approval time. These may include the waiving of select contracting or design procedures. These may require executive action and/or emergency declarations	Can improve restoration efficiency	May limit competition and may suspend environmental regulations	9, 21	-
	Lessons Learned Documentation	Documentation of all procedures for future reference and discussion of lessons learned and best practices. This information should be incorporated into the planning and training for the next event	Ability to not repeat mistakes and potentially identify new approaches to improve responses in the future. These lessons learned can be shared across agencies	Requires funding	-	-

Rapid Restoration Phase Procedure		Description	Strengths	Weaknesses	Case Study	Questionnaire
Contracting	Pre-Qualified Contracting	Contracting approaches that are completed prior to an emergency event. These can include Pre-Event Contracts, Pre-Existing Contracts and Stand-by Contracts	Reduces the response time by moving the procurement phase to before an event. Ensure qualified consultants are readily available during an emergency. Improves efficiency of the response. Leverages the skillset of personnel. Applicable to all event types	May require additional documentation to meet federal aid requirements	-	-
	Emergency Contracts	Contacting approach that is used when services are needed to immediately respond to a sudden, unexpected occurrence that poses a clear and imminent danger requiring immediate action to prevent or mitigate the loss or impairment of life, health, property, or essential public services	Can reduce the response time by expediting the procurement phase. Applicable to all event types	Can limit competition and fewer consultants may be available on short notice	16, 17	-
	Accelerated Project Delivery Contracting / Innovative Contracting	Contracting processes that emphasize rapid project completion and are alternatives to the traditional Design-Bid-Build process. These can include Design-Build and Construction Manager General Contractor. Can allow for design and construction operations to occur in parallel	Can be a highly effective approach to rapidly restore service. Can reduce overall project timeline. Applicable to all event types	May limit competition as not every company can put together an effective team. Some agencies may not be comfortable implementing these approaches and may not have the experience to manage them effectively	-	Q17

Rapid Restoration Phase Procedure		Description	Strengths	Weaknesses	Case Study	Questionnaire
Contracting	Public-Private Partnerships	A cooperative arrangement between two or more public and private sectors that work together to complete a project, typically of a long-term nature	Can group many small bridge repair projects to increase cost efficiency	May reduce competition as these are typically large contract that small to mid-size contractors may not have the resources to complete. Can be challenging to develop these partnerships following an emergency event due to time constraints	18	-
	Fast Track Contracting Provisions	These are independent of the contracting process and have been used successfully with Accelerated Project Delivery Contracts. Common provisions include Best Value Selection, A+B Bidding, A+B+C Bidding, Incentive/Disincentive Clauses, and Warranties	Can be a highly effective approach to rapidly restore service. Applicable to all event types	Some agencies may not have experience implementing these provisions	7, 13, 17	Q17
Restoration and Repair Techniques	Temporary Supports and Structures	Systems used to restore a bridge to partial or full service. These are intended as short-term solution.	Can be an effective approach to rapidly restore some service. Applicable to a wide range of events and service levels. Can improve safety of emergency responders	Not a permanent solution	2	Q15
	Modular Bridge Systems	Portable bridge systems that can be constructed to meet a variety of needs. The most common example of this is a Bailey Bridge	Can be a highly effective approach to rapidly restore service. Applicable to all event types	Typically intended as a temporary repair solution	17, 20	-

Rapid Restoration Phase Procedure		Description	Strengths	Weaknesses	Case Study	Questionnaire
Restoration and Repair Techniques	Prefabricated Components and Systems	Bridge elements that are fabricated in a controlled environment and assembled at the bridge site. Often used with rapid structural placement methods as part of accelerated bridge construction or segmental bridge construction. Can allow the superstructure and substructure construction operations to occur simultaneously	Can be a highly effective approach to rapidly restore service. Can improve quality and safety. Reduction in traffic delays. Can help with right-of-way issues	May limit competition as some contractors can be uncomfortable with this approach	7, 13, 17, 18, 22, 23, 24, 25, 26, 27	Q12, Q15
	Rapid Structural Placement Methods	Construction methods that place large portions of a bridge at a time. Often used with prefabricated components and systems as part of accelerated bridge construction or segmental bridge construction. These include the use of conventional cranes, Self- Propelled Modular Transporters, longitudinal launching, lateral bridge slides, and vertical lifting	Can be an effective approach to rapidly restore service	Typically require experienced contractor and specialized equipment and can limit competition as some contractors can be uncomfortable with this approach. Construction or transportation loading may govern the design and must be considered	8, 17, 19, 23, 24, 25, 26, 27	Q12
	Repair/Replace Decision-making guidelines	Guidelines that assist in the decision to repair or replace a damaged bridge. These guidelines are developed as part of the planning process so they are available during the emergency event to standardize the decision making	Can improve restoration efficiency	May not be applicable to all situations	13	-
	Recommended repair/restoration chart	A guide to standardize the restoration approach used based on the level of damage observed	Can improve restoration efficiency	May not be applicable to all situations	2	-

Rapid Restoration Phase Procedure		Description	Strengths	Weaknesses	Case Study	Questionnaire
Restoration and Repair Techniques	Design Process	An important and necessary step in the restoration process. A repair option is selected, and the repair is designed, including field survey and subsurface investigation, evaluation of costs, environmental impacts, permitting needs, traffic impacts, etc.	Common practice	Requires time	-	Q14
	Standard Repair Design Documents	Standard plans and specifications for common repairs	Improves consistency of design details to improve communication and minimize construction errors	Can be difficult to make these general enough to be applicable to a wide variety of situations	-	-
	Laser Scanning	Used during the rapid restoration phase for precision measurements to develop design drawings and ensure accurate fit of repairs	Applicable to a wide range of events. Can improve restoration efficiency	Requires specialized equipment and training	14	Q16
	Structural Monitoring	The use of technology, such as strain gages and data acquisition systems, to assess the variation in stress on critical structural elements during repair and restoration	Applicable to a wide range of events. Improves safety. Can improve restoration efficiency by limiting the stress on critical structural elements and preventing further damage	Requires specialized equipment and training	14, 25	-

3.2 Needs

The project team identified the following needs in the existing procedures, which are organized based on the most relevant extreme event phase. These needs were considered in the guide developed in Phase II of this project.

3.2.1 Response Planning

Need 1 ➔ *Multi-hazard response guidelines with a focus on bridges*

The results of Question 2 in the questionnaire show that over 50% of respondents indicated their agency has informal or no procedures at all for planning and rapid restoration of bridges in extreme events. In addition, approximately one third of respondents indicated they have informal or no procedures for assessment of bridges in extreme events. The literature review revealed that the procedures that exist within agencies tend to focus on assessment during a single event type (e.g., earthquakes or hurricanes). Thus, there is a need for multi-hazard guidelines that focuses on the planning, emergency assessment, and rapid restoration of bridges.

Need 2 ➔ *Lack of a plan for integrating technology in the assessment and restoration process*

The results of Question 5 in the questionnaire suggest that less than half of DOTs are somewhat or extremely likely to use technology for emergency bridge inspection. The results further indicate that agencies are more likely (i.e., “Extremely likely” and “Somewhat likely”) to use unmanned aircraft systems and autonomous boats than smart devices (e.g., smartphones and tables) even though smart devices are ubiquitous in most of our society and are currently being used by many agencies, including FEMA Urban Search and Rescue teams, to assist with emergency assessment. This indicates a need for a defined plan to integrate technology into the assessment and restoration process.

Need 3 ➔ *Inclusion of Rapid Restoration Policy in Comprehensive Asset Management Plans*

The FWHA and its partners are encouraging states to adopt Transportation Asset Management Plans (TAMPs). As states develop and mature their comprehensive asset management plans, they could use those opportunities to include policies for the rapid restoration of damaged structures in extreme events by defining their rapid restoration goals/objectives/procedures in their TAMPs. The core principles of asset management are explained in NCHRP Report 551 and can provide a useful basis for considerations in a rapid restoration policy. The core principles of asset management are:

- Decisions are policy driven
- Decisions are performance based
- Decisions include an analysis of options and tradeoffs
- Decisions are based on quality information
- Follow-up monitoring of the action is done to provide clear accountability and feedback

Need 4 ➔ *Guidance on prioritizing structures*

The results of Question 6 in the questionnaire indicates that half of respondents have documentation that details how their agency prioritizes structures for inspection. Question 7 shows that respondents believe the largest impediment to bridge inspection was prioritizing structures to inspect. The results of these two questions indicate a need for additional guidance on prioritizing structures for inspection immediately following an extreme event. The literature review discovered that several DOTs (e.g., New Hampshire, Pennsylvania, Illinois, and South Carolina) utilized a variety of prioritization methods that tend to focus on earthquake and hurricane or flooding events. Nonetheless, the project team believes a plurality of DOTs will benefit with additional guidance on this issue by summarizing best practices in a single document.

3.2.2 Emergency Assessment

Need 5 ➔ *Lack of consistency in damage assessment process and data collection*

The literature review revealed that assessment process, terminology and forms vary across transportation agencies. For example, most agencies use a multi-stage assessment process, however the number of stages and names of each stage vary across states. New York State DOT uses a four-stage process: Aerial Reconnaissance, Preliminary Bridge Damage Assessment, Special Post-Earthquake Bridge Inspection and Further Investigation. Indiana DOT uses a two-stage process: Level I, Level 2. Alaska DOT and Public Facilities uses three assessment stages: Category 1, Category 2, and Category 3 (Alipour 2016). A consistent process and terminology are important for an efficient response to large-scale events that cross state lines and utilize personnel and resources from neighboring unaffected states. *NCHRP Research Report 833* describes a recent multi-hazard assessment approach that is a possible solution to these inconsistencies (Olsen et al. 2016).

Need 6 ➔ *An explicit connection between routine procedures and extreme events procedures*

Information collected during routine procedures can be very important during an emergency bridge assessment. For example, it would be very helpful for inspectors to know if a bridge is scour critical or the location and extent of any existing damage on a bridge that may have progressed during the event. The National Bridge Inventory is now online and scour critical bridges in the database can be identified however this geospatial information may not be readily available to damage assessment professionals. Furthermore, existing assessment procedures typically do not include access to a summary of the most recent bridge inspection information during an emergency. In addition, easy access to original design documents and shop drawings can significantly reduce the downtime of a bridge as illustrated in the I-95 Chester Creek Bridge case study (see Case Study #9). Asset management tools used during both normal procedures and extreme events could provide this connection.

Need 7 ➔ *Link between the Bridge Inspector's Reference Manual (BIRM) and specific hazards*

The BIRM defines the procedures and techniques for inspecting and evaluating highway bridges in accordance with the National Bridge Inspection Standards. However, this manual is hazard agnostic and a link between relevant sections of the BIRM and specific hazards could assist inspectors during an emergency event. This could include a flowchart to provide guidance on what to look for and inspection tools to use during different event types.

Need 8 ➔ *Lack of database with guidance on assessment techniques after a specific hazard induced damage (e.g., fire event, flood, and earthquake)*

The literature review revealed many documents that provide guidance on assessment techniques for both routine and extreme events. The hazard specific assessment document must be readily available to inspectors and engineering during an extreme event. These hazard specific reference tend to be conference papers and journal publications and may not be commonly known to many agencies. A database of these various hazard specific assessment documents and techniques would help to ensure bridge assessment professionals have access to the most relevant and useful information. As an example of this gap, during our efforts on the questionnaire the project team had direct communication with a DOT seeking additional guidance and standards on assessment techniques related to bridge fire damage.

3.2.3 Rapid Restoration

Need 9 ➔ *Decision tools and guidance on the use of accelerated project delivery contracting, innovative contracting and contracting provision.*

Many of the case studies describe the value of accelerated project delivery contracting and the use of contracting provision to rapidly restore service. However, the results of Questions 12 and 17 in the questionnaire suggests that agencies are not as comfortable with these procedures as they are with procedures that focus on the construction aspects like Accelerated Bridge Construction and prefabricated replacement solutions. Decision tools and guidance on the use of proven contracting approaches and contracting provision could help agencies build their experience with these methods and improve community resilience.

Need 10 ➔ *A catalog of multi-hazard repair and restoration techniques*

Many documents in the literature review describe details on a variety of repair and restoration techniques for bridges, but these tend to focus on specific event types, bridge component or are not organized in a manner that facilitates use as a reference for rapid restoration of service. A comprehensive and well-structured catalog of repair and restoration techniques could be a useful reference for agencies during an emergency event.

Need 11 ➔ *Guidance on procurement of materials*

The results of Question 13 in the questionnaire indicate that respondents believe procurement of materials is the largest impediment to rapid restoration of service. Guidance on methods on the rapid and cost-effective procurement of material would remove this impediment.

Need 12 ➔ *Central clearinghouse for after action reports or case studies for major event*

After action reports (AARs) are brief documents used by FEMA Urban Search & Rescue teams and other agencies (Matherly et al. 2014) to document the methods and procedures that worked well and the areas that require improvement. Collecting these reports in a single location and securely sharing them within and across agencies can allow agencies to improve their procedures for major events, defined as an event that exceeds a certain threshold of either repair costs, down time, or casualties.

3.3 Recommendations

In this section procedures are recommended for response planning, emergency assessment, and rapid restoration of service of bridges in extreme events. The proposed procedures are intended to be appropriate for nationwide adoption. The key components of the proposed procedures include: (i) a “First You Plan” approach; (ii) emphasis on communication and collaboration; (iii) promoting accelerated versions of familiar project delivery methods; (iv) multi-level assessment process; (v) appropriate use of technology with fail-safe backup plans, and (vi) promote ABC construction practices. For clarity, recommendations made in this document are numbered and identified with a bold arrow.

3.3.1 Key Recommendations for Planning

Recommended Planning Action 1 ➔ *Develop a communication framework and maintain regular contact with essential personnel throughout one’s agency and in other agencies*

Clear communication lines are critical for an efficient response. Regular communication during non-emergency conditions helps foster relationships and can improve the response effort during extreme events. This communication framework should include methods to keep the public informed as much as possible and should include, alert systems, push notifications, crowdsourcing, and the use of social media platforms.

Recommended Planning Action 2 ➔ *Involve stakeholders from relevant agencies in the discussions and preparatory tasks*

All relevant parties must have a voice in the decision-making process. This can be a challenge as part of a response to an emergency event. Building and maintaining relationships between stakeholders during non-emergency conditions helps all parties understand each other's major concerns. This communication and understanding and can minimize impediments during the response to an extreme event.

Recommended Planning Action 3 ➔ *Provide regular (annual, bi-annual) training to first responders and highway bridge inspectors*

Emergency personnel must be properly prepared for an emergency situation. In many cases, to be able to efficiently complete inspections, transportation agencies will need to rely on personnel who do not routinely perform inspections, such as design engineers. These personnel should be identified and given the appropriate level of training, so they are prepared to respond.

Recommended Planning Action 4 ➔ *Periodic mock events should be held so that problems can be identified and resolved in non-emergency situations*

Some extreme events (e.g., earthquakes) are rare and many DOT personnel do not have experience responding to these types of events. Mock events are excellent approaches to practice responding to these types of events. These events help with team building and foster relationship both intra and inter-agency. In addition, these events allow responders to practice with equipment that may not be used regularly, practice communication lines, and identify challenges in the process that need be resolved prior to an extreme event.

Recommended Planning Action 5 ➔ *Collect and document existing information to define a baseline condition*

The project team recommends that transportation agencies start with a set of records (e.g., database, preferably geospatial) as the core technology that includes as much found asset condition information as the agency can afford. MAP-21 legislation is requiring DOTs to acquire more of this information in geospatial inventories. This baseline condition database would be available at the emergency event command center and if the communications support it, in the field. Information that could be useful in the field includes a summary of the most recent inspection report with details about pre-existing damage and the scour critical rating of the bridge. This database can be queried in real-time for state DOT inspectors and responders. As the emergency and safety information is being accrued and processed, there could be secure access to the information for public alerting.

Recommended Planning Action 6 ➔ *Develop an Assessment Prioritization Plan*

This plan will include a list of vulnerable structures, critical structures and critical routes that must be opened to traffic first to promote community resilience. These lists may vary depending on the extreme event types, so multiple event-dependent lists may be needed. For earthquakes, which provide no advance warning, the plan should include an algorithm to prioritize assessments based on proximity to the epicenter, age of the bridge and condition of the bridge (See Case Study #3 Nisqually Earthquake).

Recommended Planning Action 7 ➔ *Develop pre-qualified contracting approaches.*

Qualified consultants must be readily available during an extreme event. Pre-qualified contracting approaches are completed prior to an emergency event and include pre-event contracts, pre-existing contracts, and emergency on-call contracts. These approaches can reduce the response time and maintain a competitive bid process in any type of extreme event.

Recommended Planning Action 8 ➔ *Identify potential emergency funding sources and prepare required documents*

This information will help secure funding rapidly to improve response effectiveness. In addition, this preparation can ensure that the needed information is collected during the event to secure funding. Agencies must be aware that the requirements vary between funding sources and may change over time.

Recommended Planning Action 9 ➔ *Implement preventative measures*

These actions are taken prior to the event to minimize the impact on the community. These measures vary in scope and can differ for extreme event type. Small scope preventative measures can include the installation of debris deflectors, debris catchers, scour countermeasures and impact barrier protection. Larger scope measures can include closed-circuit monitoring. Highly vulnerable bridges may require extensive retrofit of local components or full bridge replacement. These measures improve community resilience and can reduce or eliminate completely the level of damage experienced during an extreme event.

Recommended Planning Action 10 ➔ *Develop Staging/Asset Positioning Plans*

Asset positioning plans describe and define the strategic placement of important assets for rapid access and use. These plans ensure materials, equipment and personnel are available during an extreme event. As an example, Hawaii DOT positions their heavy equipment in accessible high ground locations prior to a hurricane to ensure the equipment is available to clear roads of debris.

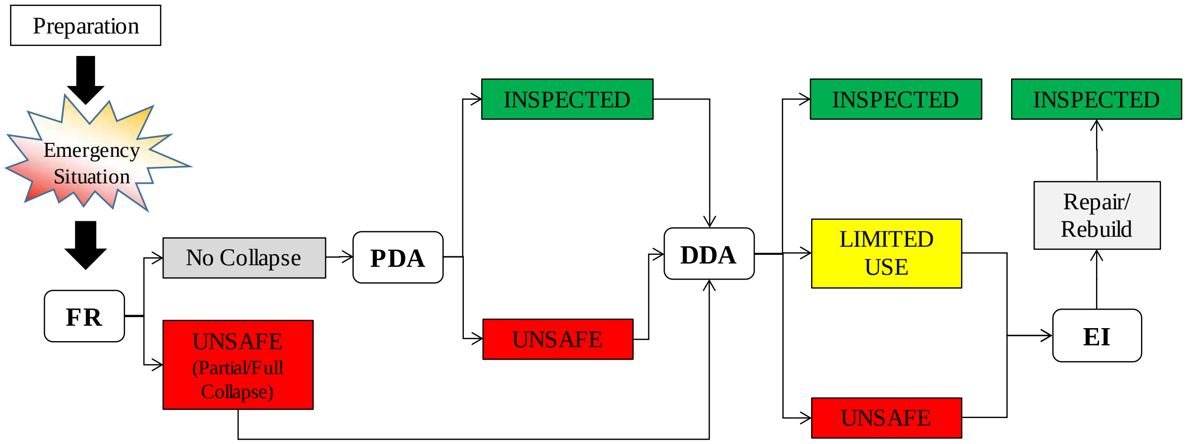
Recommended Planning Action 11 ➔ *Develop repair/replace criteria*

The decision to repair or replace a damaged bridge will depend on several factors including: the extent of damage, the remaining expected service live of the bridge, the agencies' broader vision for the transportation network, and the effects on traffic levels. Defining clear criteria before an event can expedite the recovery, improve community resilience, and may help an agency achieve its broader vision for the region.

3.3.2 Key Recommendations for Assessment

Recommended Assessment Action 1 ➔ *Implement a multi-level assessment process*

A hierarchy of assessment levels can ensure an efficient response and improve situational awareness to assist with event response and recovery planning to a broad range of events. The project team recommends using the assessment framework described in *NCHRP Research Report 833* (Figure 2-5).



UNSAFE = The structure requires further evaluation in the next assessment stage prior to being open to traffic.
LIMITED USE = Potentially dangerous conditions are believed to be present and usage is restricted to ensure public safety.
INSPECTED = The structure appears to be in the same condition as it was prior to the event.

Figure 3-1. Assessment Stages and Subsequent Primary Level of Coding (Olsen et al. 2016). Note FR = Fast Reconnaissance, PDA = Preliminary Damage Assessment, DDA = Detailed Damage Assessment, and EI = Extended Investigation.

The framework defines four assessment levels: Fast Reconnaissance (FR), Preliminary Damage Assessment (PDA), Detailed Damage Assessment (DDA) and Extended Investigation (EI). This multi-level process leverages the existing skillset of personnel and can have maintenance and inspection crews perform Preliminary Damage Assessments while engineers and personnel with appropriate training can perform Detailed Damage Assessments.

Recommended Assessment Action 2 ➔ *Implement preliminary damage forms and visual assessment aids*

These can include photos, maps, videos, and diagrams that can be used by all responders in their emergency condition assessment and to identify/classify levels of damage. *NCHRP Research Report 833*includes examples of assessment forms for both bridges and culverts. When possible, these forms and aids should be made available in digital formats so that these may be filled out on portable digital devices and, as a last resort, on paper in the case that communication networks be unavailable. The digital format facilitates upload into an asset management system and can allow for real-time situational awareness to field personnel.

Recommended Assessment Action 3 ➔ *Implement a fail-safe response procedure that allows for locally generated electronic Preliminary Damage Assessment forms or hard copies of the assessment forms that can be hand delivered to the command center*.

The project team recognizes that the use of paper forms is being replaced by the use of smart devices with networking and even cloud computing support (e.g., smartphones and tablets that are equipped with high-resolution cameras, GPS, networking, and computing capability). In this project, the team aims to recommend a guideline for leveraging the use of these connected smart devices to aid the response process and provide real-time situational awareness to all relevant personnel.

Recommended Assessment Action 4 ➔ *Implement specialized technology-based assessment as available and appropriate.*

Specialized technology-based assessment can provide a rapid assessment rate and/or information not readily available from other inspection techniques. These approaches include lidar, photogrammetry, UASs, satellite imagery, and sonar. These methods can be part of the Fast Reconnaissance, Detailed Damage Assessment or Extended Investigation assessment level and are applicable to any type of extreme event.

3.3.3 Key Recommendations for Rapid Restoration

Recommended Rapid Restoration Action 1 ➔ *Implement expedited approval processes*

These procedures often follow the normal day-to-day process but have higher priority to reduce approval time and improve efficiency during an extreme event. These may include the waiving of select contracting or design procedures and may require executive action and/or emergency declarations.

Recommended Rapid Restoration Action 2 ➔ *Implement accelerated project delivery contracting as appropriate*

Accelerated project delivery contracting emphasize rapid project completion and are alternatives to the traditional Design-Bid-Build process. These can include Design-Build and Construction Manager General Contractor. This type of contracting approach can be a highly effective way to rapidly restore service and can reduce overall project timeline and is applicable to all event types.

Recommended Rapid Restoration Action 3 ➔ *Include fast track contract provision that emphasize rapid early delivery*

Fast track contract provisions are independent of the project delivery method and have been used successfully with Accelerated Project Delivery Contracts. Common provisions include Best Value Selection, A+B Bidding, A+B+C Bidding, Incentive/Disincentive Clauses, Warranties, and Lane Rentals. These can be a highly effective approach to rapidly restore service and are applicable to all extreme event types.

Recommended Rapid Restoration Action 4 ➔ *Utilize temporary supports, temporary structures and/or modular bridge systems to restore some service to the public as soon as possible while a permanent solution is pending*

These common and proven systems are used to restore a bridge to partial or full service for any type of extreme event. These are intended as short-term solutions and can provide a variety of services. For example, temporary supports and shoring can provide access to emergency vehicles and improve safety for emergency responders. Temporary supports and structures can provide access to a few lanes of traffic. Portable modular bridge systems (i.e., a Bailey Bridge) can restore temporary access to all traffic lanes.

Recommended Rapid Restoration Action 5 ➔ *Utilize prefabricated components/systems and rapid structural placement methods (i.e., ABC techniques) as much as possible*

Prefabricated bridge components are typically fabricated in a controlled environment and assembled at the bridge site, and often used with rapid structural placement methods as part of accelerated bridge construction or segmental bridge construction. These are a proven and highly effective approach to rapidly restore service and allow for superstructure and substructure construction operations to occur simultaneously. Rapid structural placement methods can include the use of conventional cranes, longitudinal launching, lateral bridge slides, vertical lifting, and Self-Propelled Modular Transporters. These construction methods can allow for large portions of a bridge to be constructed at a time and can improve quality and safety, reduce traffic delays, and limit right-of-way issues.

Recommended Rapid Restoration Action 6 ➔ *Considering monitoring severely damaged bridges*

Structural monitoring can be used in the short-term during the assessment phase or in the long-term during the restoration phase to improve safety and monitor the stability of a damaged bridge. During the assessment phase, a total station can be used to observe and monitor motion of the bridge. During the recovery phase, more advanced systems that provide localized information such as strain gages and data acquisition systems, can be used to assess the variation in stress on critical structural elements and ensure the damage does not progress while repairs are being implemented. These approaches are applicable to a wide range of events and can improve restoration efficiency by limiting the stress on critical structural elements and preventing further damage.

Recommended Rapid Restoration Action 7 ➔ *Document best practices and lessons learned and update planning, assessment, and rapid restoration procedures.*

The project team recommends that agencies implement a formal process to build and retain institutional knowledge regarding best practices and lessons learned following extreme events. This can be accomplished with case studies or after-action reports which should include input from all stakeholders. These reports must be housed in a secure and accessible location for reference during the planning phase to improve extreme event response procedures.

Chapter 4: Development of the Guide

This chapter provides an overview of *NCHRP Research Report 1098: Guide for Response Planning, Assessment, and Rapid Restoration of Service of Bridges in Extreme Events* and describes the key considerations in developing the guide.

4.1 Introduction

The guide focuses on a typical extreme event cycle with three main phases: planning, response/assessment, and rapid restoration. Figure 4-1 shows how the NCHRP 14-45 Guide sections (See *NCHRP Research Report 1098*) aligns with the National Disaster Recovery Framework (Homeland Security 2016), which divides an event into Pre-event Planning, Response and Recovery. The guide is applicable to a variety of extreme events including earthquakes, tsunamis, hurricanes/storm surge, flooding/scour, fires, collisions, and man-made events.

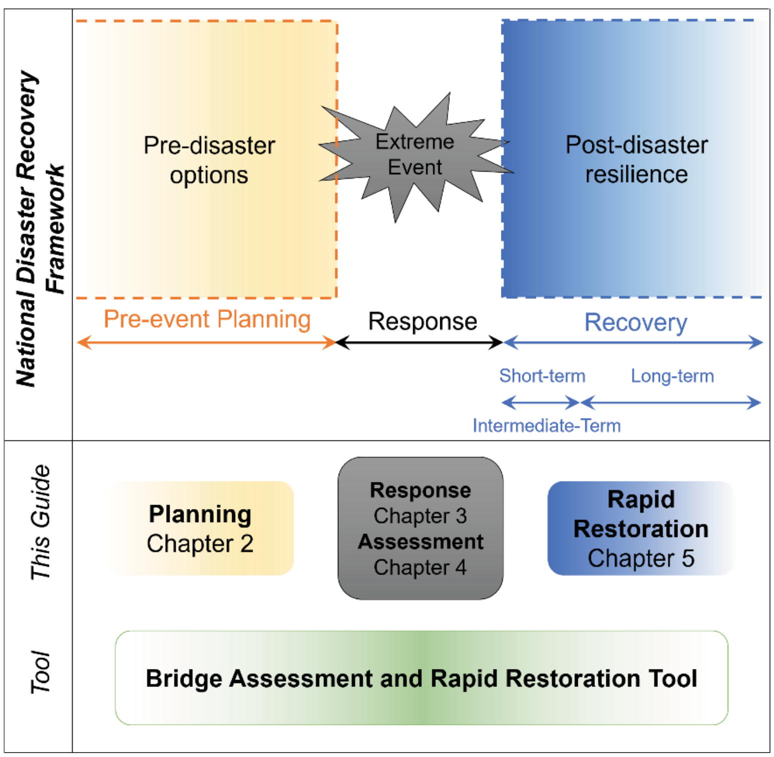


Figure 4-1. **NCHRP Research Report 1098: Guide for Response Planning, Assessment, and Rapid Restoration of Service of Bridges in Extreme Events *Components and Alignment with the National Disaster Recovery Framework (Homeland Security 2016).***

4.1.1 Primary Audience

The primary audience for the guide includes state DOTs of all sizes: small local agencies, states DOTs, and federal organizations. More specifically, the managers, engineers, and inspection of these organizations who are responsible to plan, coordinate, and administer emergency event response and recovery efforts.

4.2 Key Considerations

The procedures described in the guide were selected because they align with the following key considerations:

- ***Proven industry common practices*** – The recommended procedures leverage and build upon NCHRP Project/Synthesis Reports, AASHTO guidelines, and transportation agency Emergency Response Plans. These documents include:
  - *NCHRP Synthesis 438: Expedited Procurement Practices for Emergency Construction Services* (Gransberg et al. 2012),
  - *NCHRP Synthesis 497: Post-Extreme Event Damage Assessment and Response for Highway Bridges* (Alipour 2016),
  - *NCHRP Report 753: A Pre-Event Recovery Planning Guide for Transportation* (Bye et al. 2013),
  - *NCHRP Report 777: A Guide to Regional Transportation Planning for Disasters, Emergencies, and Significant Events* (Matherly et al. 2014),
  - *NCHRP Research Report 833: Assessing Coding and Marking of Highway Structures in Emergency Situations* (Olsen et al. 2016),
  - *AASHTO Guide for Bridge Preservation Actions* (AASHTO 2021), which is based on *NCHRP Research Report 950: Proposed AASHTO Guides for Bridge Preservation Actions* (Hearn 2020).
- ***A "First You Plan" approach with emphasis on communication and collaboration*** – Planning is essential for an efficient extreme event response and resilient communities. The procedures provide guidance on the development of an effective communication and coordination framework and implement effective training programs and pre-event planning tasks.
- ***A four-level assessment process* -** The four levels are: Fast Reconnaissance (FR), Preliminary Damage Assessment (PDA), Detailed Damage Assessment (DDA) and Extended Investigation (EI). FR and PDA are rapid assessments to determine the extents of damage to the region and provide data to guide resource prioritization and recovery efforts. DDA and EI are thorough assessments to ensure public safety. DDAs provide information to prioritize the restoration of service efforts and can be used by managers to assist with repair/replace decisions. EIs provide details on the repairs needed to restore service.
- ***Appropriate use of technology with fail-safe backup plans*** – Current technologies can provide near real-time bridge condition updates based on FR and PDA to all personnel, and especially to key decision makers. This rapid transfer of information is essential for a rapid response. At the same time, some technologies may be inoperable during an extreme event, and a fail-safe backup plan must also be established.
- ***Promoting accelerated versions of familiar procurement procedures*** – Industry common practice is to follow the normal day-to-day procurement process but increase the priority of the steps to reduce approval time and improve efficiency during an extreme event. This expedited process may include waiver of or expedited processes for select contracting procedures (such as pre-event contracts, pre-existing contracts, and stand-by contracts) and may require executive action and/or emergency declarations to enable these contracting methods.
- ***Promote Accelerated Project Delivery Methods and Accelerated Bridge Construction (ABC)*** – Accelerated project delivery methods and ABC approaches have proven to reduce construction

timelines and traffic disruption. These practices include fast-track project delivery methods (e.g., Design-Build), bidding and contracting that incentivizes compressed project schedules (e.g., A+B Bidding, A+B+C Bidding, Incentive/Disincentive clauses), and construction methods (e.g., prefabricated components/systems and rapid structural placement).

4.3 Organization of the Guide

The guide is organized into five chapters that provide direction across all phases of the extreme event cycle. The sections are described below.

4.3.1 Chapter 1: Introduction

This section of the guide provides background, describes key terms, and offers an overview of the guide. In addition, this section introduces users to the Bridge Assessment and Rapid Restoration Tool (BARRT), which can assist state DOTs in all phases of an extreme event.

4.3.2 Chapter 2: Pre-Event Response Planning and Preparedness

Chapter 2 of the guide presents procedures to be implemented well in advance of an extreme event to facilitate rapid restoration of service of bridges and thus improve the long-term resiliency of the network. State DOTs are guided to revise or develop an Emergency Operations Plan (EOP) to define the operations at all phases of an event. Elements to be included in the EOP are command, communication, and coordination plans; resilient and preventative measures; inspection and assessment preparation; planning for restoration actions; training; and defining a post-event evaluation process. Additional details of these elements are shown in Figure 4-2.

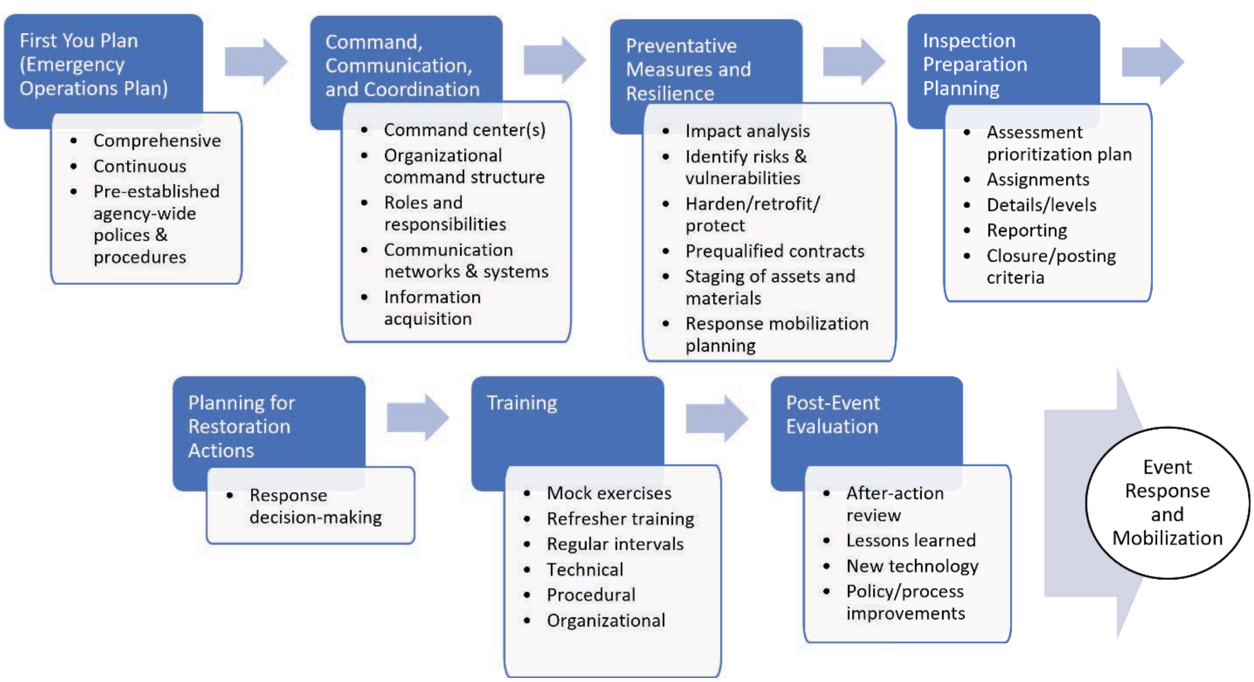


Figure 4-2. Elements of Pre-Event Planning and Preparation

4.3.3 Chapter 3: Event Response and Mobilization

This section of the guide outlines steps and actions that state DOTs should take once they become aware that an extreme event has occurred or is imminent. Figure 4-3 illustrates these key steps which include: Determining the response level to the event (see Table 4-1); Determining the personnel and resource needs; Re-evaluating assessment and restoration priorities based on the current field conditions; Communicating with personnel, stakeholders and the public; Mobilization of resources, and; Requesting funding (see Table 2-2) and additional resources as needed. A tool that can assist state DOTs during this phase is the Emergency Event Action Plan (EEAP) (see Chapter 5.4.2). This tool will generate an initial suggested response plan that can be used to direct the event response and mobilization activities.

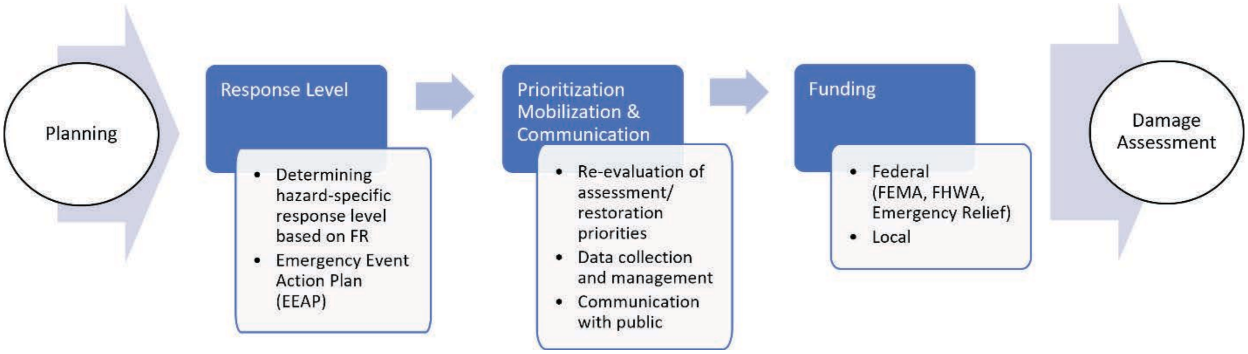


Figure 4-3. Response and Mobilization Elements

Table 4-1. Description of Response Levels and Corresponding Mobilization Levels (Adapted from Olsen et al. 2016)

Level	Description
Level I	Regular inspectors in the affected region(s) directly proceed from FR to PDAs and DDAs as needed. Teams are mobilized when the ME determines that some damaged has occurred based on FR observations.
Level II	State DOTs complete PDAs with their maintenance crews and DDAs with their inspection crews. Additional personnel like engineers are placed on call and mobilized to assist with PDAs when ME deemed necessary.
Level III	Inspectors focus on DDAs and maintenance crews, engineers, and others are immediately mobilized to perform PDAs. Inspectors from other regions may be called upon to assist as needed. External consultants from local firms (who are appropriately trained) may also be utilized. Federal assistance and coordination may also be required.
Level IV	In addition to the mobilization strategy in Level III, the State DOTs requests immediate assistance from inspectors, maintenance crews, engineers, and external consultants from other regions to assist with PDAs. Significant federal assistance will be necessary.

FR = Fast Reconnaissance; PDA = Preliminary Damage Assessment; DDA = Detailed Damage Assessment; ME = Managing Engineer

4.3.4 Chapter 4: Damage Assessments

Chapter 4 of the guide provides direction on bridge damage assessments. Key components of the damage assessment process are shown in Figure 4-4 and include: Inspection logistics and coordination (see. Figure 4-5); Refresher training for assessment personnel; Re-evaluation of assessment priorities based on field conditions, and A four-stage structural assessment process (see Figure 4-6).

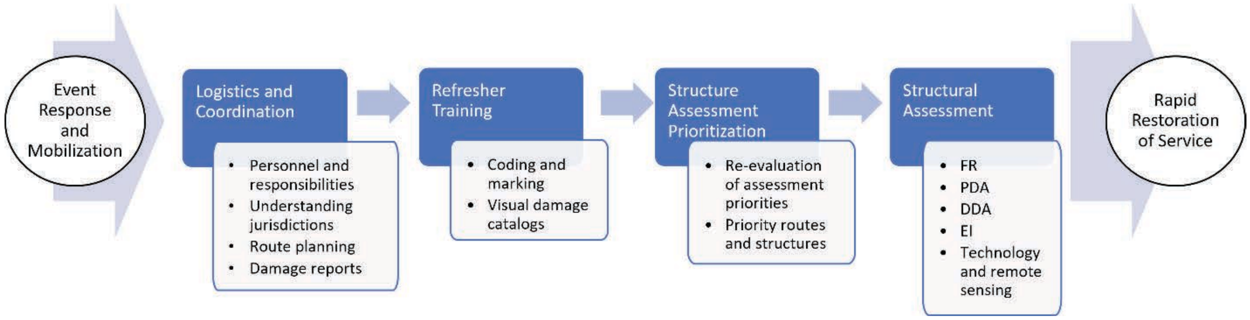


Figure 4-4. Key Components of the Damage Assessment Process

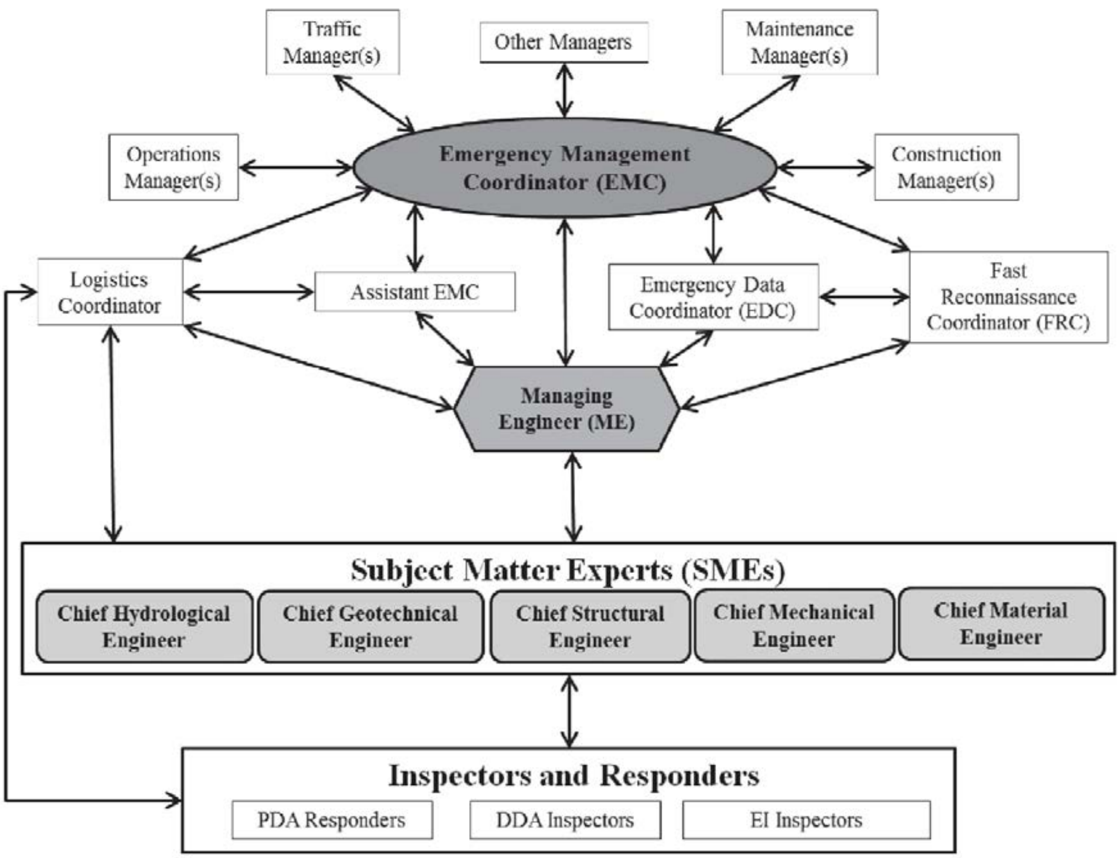


Figure 4-5. Logistics and Coordination of Damage Assessments (Modified from Olsen et al. 2016)

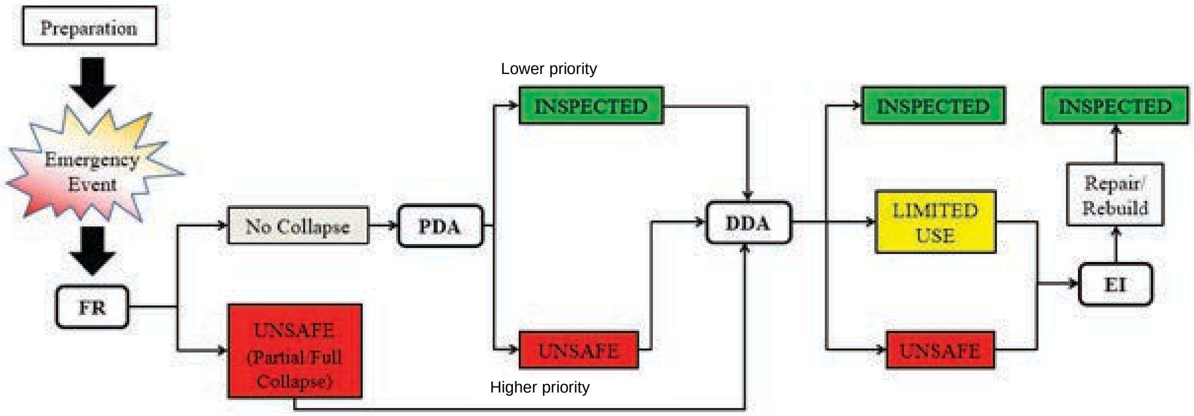


Figure 4-6. Emergency Assessment Process (Modified from Olsen et al. 2016).

4.3.5 Chapter 5: Rapid Restoration of Service

The final section of the guide provides direction on rapid restoration of service. Key components of this section are shown in Figure 4-7 and includes guidelines for: Rapid restoration priorities; Short/Intermediate-term recovery efforts; Long-term recovery efforts, and; Procurement and contracting provisions (see Table 4-2). A tool that can assist state DOTs during this phase is the Bridge Specific Action Plan (BSAP) (see Chapter 5.4.3). This tool will generate a suggested action plan based on the documented damage on a specific bridge.

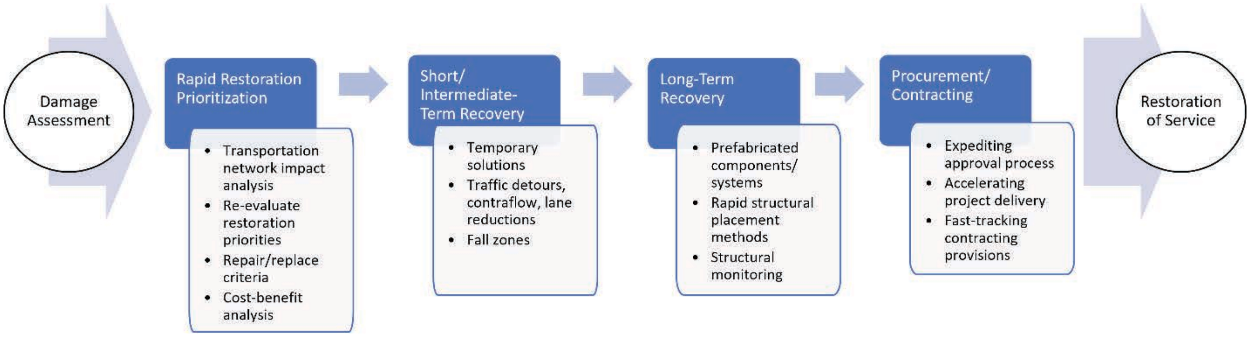


Figure 4-7. Key Components of the Rapid Restoration Process

Table 4-2. Rapid Restoration Contract Provisions and Contract Selection Options

Method	Description	Benefits	Challenges
Best Value	• Contractor(s) selected based on best price and best qualifications, thus creating a "best value" • Selection can be determined based on a point system where contractors can score more points based on their technical expertise and cost	• Most qualified contractor selected • Pairs well with ABC projects	• Requires contractors to maintain a special list of qualifications • Low bid contractors may not always qualify
A+B Bidding (Culmo 2011, WSDOT 2016, MNDOT 2008)	• A+B Bidding works by looking at the cost (A) and the time (B) when making a contractor decision This contracting method was used after the Skagit River Bridge Collapse in Washington. Washington DOT used this process paired with early milestone completion incentives, which helped to expedite the repair process	• Can reduce project time • Contractors required to develop a well-conceived schedule • Improved coordination between prime and sub-contractors	• Requires additional expertise to prepare contract clauses. • May require more resources for contract administration, including more hours and over-time budge for staff • Contract changes are magnified, too many changes nullify advantages
A+B+C Bidding	• Adds a milestone (C) component to A+B Bidding • User costs are factored into the C component, which often includes incentives or disincentive if the project milestones are or are not met on time • The dollar value of these incentives/disincentives are based on these user costs to incentivize a quicker completion date	• Quicker completion date • Considers the costs associated with delays and closures for motorists during construction	• Requires additional expertise to prepare contract clauses. • May require more resources for contract administration, including more hours and over-time budget for staff • Contract changes are magnified, too many changes nullify advantages
Incentives and Disincentives (I/D Clause) (Culmo 2011)	• Can be added to penalize the contractor or provide financial incentives to complete and meet set project milestones • Incentive and disincentive amounts are usually the same • If not, recommended that the incentive is less than the disincentive. • Actual amounts can be determined by the road user costs	• Reduced construction time • Potential for lower contract administrative costs • Improved control of project acceleration compared to A+B[3]	• May require additional funding • Contract changes can lead to disputes regarding incentive payments
Lane Rentals (MNDOT 2008)	• A means to minimize impact to road users by minimizing the delays caused by construction. • The contractor is charged for the amount of time a lane is out of service.	• Improved Coordination of prime and sub-contractors • Minimize impact to traveling public • Improved public perception due to fewer un-utilized lane closures	• Extra effort by staff to monitor lane rental • Negotiating lane rental adjustment can be difficult with contract changes • Potential added cost to the project

Chapter 5: Development of the Tool

This chapter provides an overview of the Bridge Assessment Rapid Restoration Tool (BARRT), a tool to support implementation of the guide.

5.1 Background and Motivation

BARRT was developed to complement *NCHRP Research Report 1098: Guide for Response Planning, Assessment, and Rapid Restoration of Service of Bridges in Extreme Events.* State DOTs often use several platforms and methods to manage their planning, assessment, and rapid restoration procedures. Multiple platforms can create confusion regarding the current versions, where specific items are stored, and who maintains each resource. Therefore, a unified platform that contains links, documents, and manuals of the State DOT's resources is advantageous to allow for quick communication and action. The Bridge Assessment and Rapid Restoration Tool (BARRT) was developed to serve as this platform, which contains information on planning, assessment, and rapid restoration for bridges and culverts. BARRT is customizable and can be updated to house pre-existing procedures and documents in addition to newly developed information.

5.2 Description of the Tool

BARRT is comprised of two types of tools: interactive PowerPoint tools and Excel/Word Based tools. A brief summary of all tools within BARRT is tabulated in Table 5-1. BARRT is designed to serve as a quick reference for state DOTs through the interactive PowerPoint-based tools and as a starting place for planning, assessment, and restoration options through the Excel/Word based tools.

BARRT is designed to function with varying levels of function based on available connectivity. Almost all features of BARRT will operate without an internet connection; only links to website or online cloud services require the use of the internet. The interactive PowerPoint platform and the corresponding tools can be saved on a State DOT agency shared network or downloaded to individual devices, depending on connectively needs. Thus, BARRT can operate without stringent connectivity requirements.

The Interactive PowerPoint tools are information-based and are organized in a website-like interface where users click on a series of tabs to navigate to different slides that contain information or links to relevant documents or forms. This content is divided into five sections including planning, assessment, rapid restoration, contracting, and help guide/tutorials.

The Excel/Word based tools are accessed from the main BARRT platform but run using Visual Basic for Applications (VBA) code. The code allows users to provide a series of inputs to generate a uniform form, recommendation, or list of suggested actions, depending on the specific tool. There are five tools accessible through BARRT including: Emergency Event Action Plan (EEAP), Bridge Specific Action Plan (BSAP), Case Study tool, Status Form, and Contact Form.

To use all features within BARRT, users need a Windows Operating System that is equipped with full versions of Microsoft Office (Word, PowerPoint, and Excel). The core BARRT platform runs within Microsoft PowerPoint but directly links to features within Excel and Word as needed for other tools. BARRT is currently not compatible with Mac OS X, even with Microsoft Office for Mac. Tablets that run IOS may be used to access several of the BARRT tools, but are unable to run the more advanced tools, which rely on macros in Microsoft Excel and Word to run Visual Basic for Applications (VBA) code to operate. (Note that users do not need to have a knowledge of VBA to use the tools).

Table 5-1. Tools within BARRT

Type	tool	Description or Purpose
Interactive PowerPoint Tools	Planning	Contains flowcharts and processes used to prepare for an emergency event. It is complemented by the EEAP tool.
	Assessment	Outlines typical assessment methods, suggested forms, and anticipated outcomes for each type of assessment. Forms are available for download (digitally or for printed copies), making is easier to share common forms across agencies.
	Rapid Restoration	Presents common restoration procedures that may be implemented for extreme event use. It is complemented by the BSAP tool.
	Contracting	Describes common contracting and procurement methods that are used in emergency situations. Provides some examples of these methods, and placeholders for transportation agencies to easily upload agency-specific pre-existing forms.
	Help Guide/ Tutorials	Documentation on how to use the tool and how to customize and update it based on a specific State DOT's need.
Excel/ Word Based Tools	Emergency Event Action Plan (EEAP)	Creates a high-level plan based on the characteristics of the specific event. Aids in the determination of appropriate response levels and courses of action in the response phase.
	Bridge Specific Action Plan (BSAP)	Supports the restoration plan of a specific structure based on the nature and extent of damage and type of bridge. This tool links repair methods discussed in AASHTO's *Guide to Bridge Preservation Actions* and other primary sources to NBI elements with a user input form.
	Case Study tool (CST)	A platform to share and explore information from prior events and create new examples based on current events.
	Status Form	A template form to update the changing emergency response status to share with stakeholders. This template can be used to reflect a time-history of the response methods, current operations, resources deployed, and contact information of those with additional information.
	Contact Form	A template for transportation agencies to update their contact information that could be potentially shared with other agencies for transparency and general information sharing.

5.3 BARRT User and Developer Guides

Two guides were developed to assist state DOTs on how to use BARRT: user guide and developer guide. These guides are included in the *Bridge Assessment Rapid Restoration Tool (BARRT) Training Manuals* and includes Part I Users Guide and Part II Developer Guide.

The User Guide outlines the overall interface, tool functions, and offers tips. The user guide walks users through each of the tools and includes figures to provide a visual representation of how to navigate the tool. If users wish to customize any features of the tool, then the Developer Guide should be referenced.

The developer guide provides information for how to edit each of the individual tools, including adding or removing content, uploading unique links and forms, and gives basic direction for editing the VBA code. Many users can use its full features without customization. However, for complete integration with existing procedures, state DOTs may have the desire to customize the tool to meet their specific needs.

5.4 Summary of Individual Tools

5.4.1 Interactive PowerPoint-based tools

The five tools included in the interactive PowerPoint-based tools are accessed from the main BARRT homepage (Figure 5-1). These tools contain general information about the specific topics, provide links to resources (either saved in the tool library housed within BARRT or from the internet), and include downloadable templates. The planning, assessment, rapid restoration, and contracting tools contain the same general information included in *NCHRP Research Report 1098* but repackaged into a different format. Additionally, downloadable forms and placeholders for state DOTs to upload their own forms and content are solely included in BARRT. In addition, the Excel/Word based tools can be launched from the main BARRT homepage.

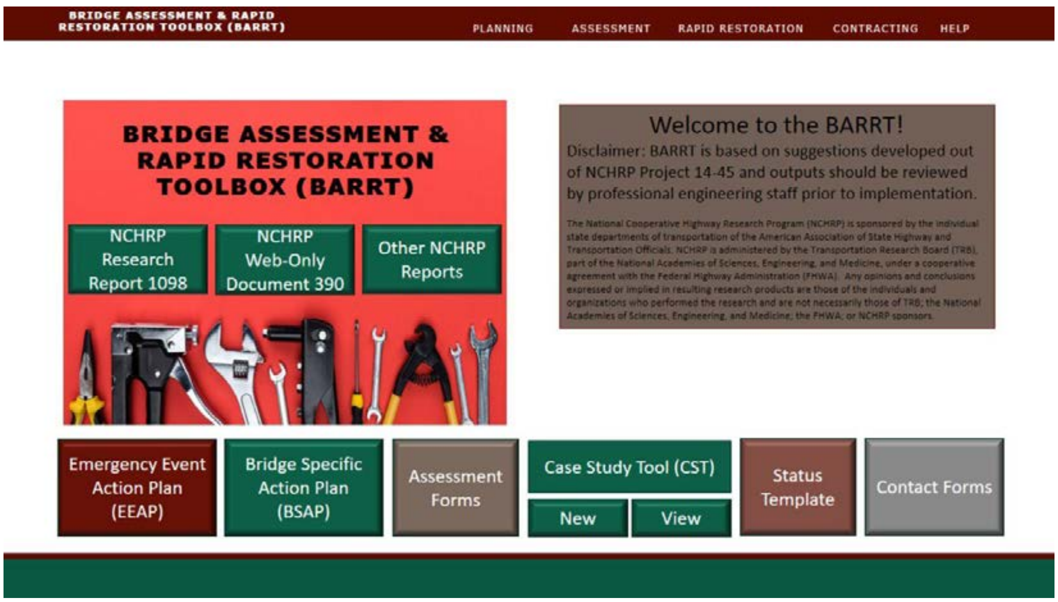


Figure 5-1. BARRT Main Homepage

5.4.2 Emergency Event Action Plan

The Emergency Event Action Plan (EEAP) provides users with a suggested action plan for their specific extreme event based on the severity of the event. The action plan is formatted as a Word document that can be edited as needed before release. To generate an EEAP. the user begins with inputting the type of emergency or extreme event, the event location, then indicating the event classification and timeline. With this information, EEAP extracts information from a series of Excel worksheets (hidden within the EEAP Excel Workbook) to generate the action plan in Microsoft word (Figure 5-2). Users can customize specific inputs or outputs within the Excel Workbook to reflect their own regional requirements or practices.

Figure 5-2. EEAP User Workflow

The generated action plan is organized into eight main headings: summary, action, event specific guidance, expected damage, immediate actions, suggested restoration techniques, contracting, and priorities. Each section includes event-specific guidance for users and was based on current procedures identified during the literature review. Figure 5-3 shows an example of an EEAP input. Figure 5-4 and Figure 5-5 show the corresponding output.

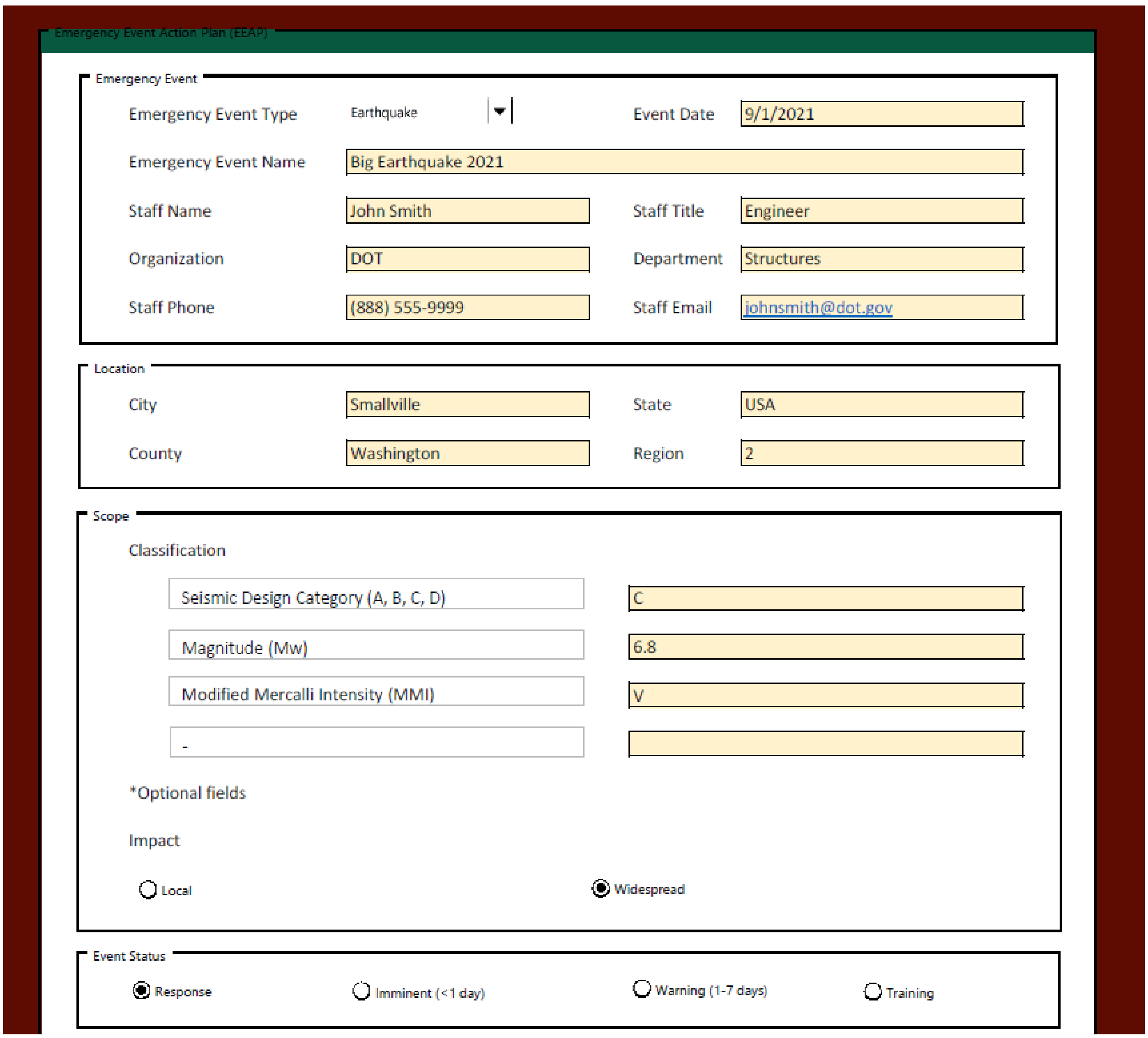


Figure 5-3. EEAP Input for Magnitude 6.8 Earthquake

This document was produced as part of NCHRP Project 14-45: Guidelines for Response Planning, Assessment, and Rapid Restoration of Service of Bridges in Extreme Events. The National Cooperative Highway Research Program (NCHRP) is sponsored by the individual state departments of transportation of the American Association of State Highway and Transportation Officials. NCHRP is administered by the Transportation Research Board (TRB), part of the National Academies of Sciences, Engineering, and Medicine, under a cooperative agreement with the Federal Highway Administration (FHWA). Any opinions and conclusions expressed or implied in resulting research products are those of the individuals and organizations who performed the research and are not necessarily those of TRB; the National Academies of Sciences, Engineering, and Medicine; the FHWA; or NCHRP sponsors.

EMERGENCY EVENT ACTION PLAN

NOTE: THIS IS AN AUTOGENERATED REPORT AND NEEDS TO BE REVIEWED BY OTHERS PRIOR TO USE.

SUMMARY

REPORT DATE	EVENT NAME	EVENT DATE
12/6/2021	Big Earthquake 2021	9/1/2021
LOCATION	**COUNTY**	**REGION**
Smallville, USA	Washington	2
EVENT TYPE	**STATUS**	**RESPONSE LEVEL**
Earthquake	Response	IV

STAFF MEMBER NAME	ORGANIZATION/DEPARTMENT
John Smith, Engineer	DOT, Structures
STAFF PHONE	**STAFF EMAIL**
8885559999	johnsmith@dot.gov

RESPONSE LEVEL ACTION

Data for this earthquake in Washington County, USA was pulled from the USGS, including the moment magnitude of 6.8 and moment magnitude intensity of 5. The observed damage from the initial reports is Widespread. The Response Level is IV. At Response Level IV, a large number of structures are subjected to damage, and prioritization should be updated based on bridge importance, especially those that connect lifeline infrastructure, public facilities, and relevant economic activities. Therefore, fast reconnaissance and preliminary damage assessments are required. Detailed damage assessments are arranged for critical structures.

SCOPE OF CONCERN

Based on the intensity mapping, the default radius of concern for this event is greater than 80 miles.

Please note this is an initial inspection radius. If damage is observed outside this radius, the radius should be increased.

EXPECTED DAMAGE

Page 1

Figure 5-4. Hypothetical example of EEAP Output for Magnitude 6.8 Earthquake Page 1

Structural damage, including collapse, are expected.

IMMEDIATE ACTION

The state's Incident Command System will be activated for this high-level response to ensure coordination of effort among regions, incident command, and other agencies. All available personnel should be mobilized. Preliminary damage assessments shall be conducted immediately. Inspection results, including marking and coding results, are critical for local traffic rerouting and should be updated in real-time.

The managing engineer shall arrange for detailed damage assessments of all critical structures that are within the radius of concern as soon as possible. Detailed damage assessments shall follow the same criteria presented in Response Level III.

SUGGESTED RESTORATION TECHNIQUES

Elements and system-level repairs are expected for impacted bridges. Bridge replacement is considered for partially or fully collapsed bridges. Temporary or long-term closures, structures, and rerouting are expected.

CONTRACTING

Long-term external bridge inspection, repair, and construction contracts are expected. ABC construction should be considered.

SIGNATURES

Revised By	Print Name:	______________________	Date:	____________
	Signed Name:	______________________	Date:	____________
Approved By	Print Name:	______________________	Date:	____________
	Signed Name:	______________________	Date:	____________

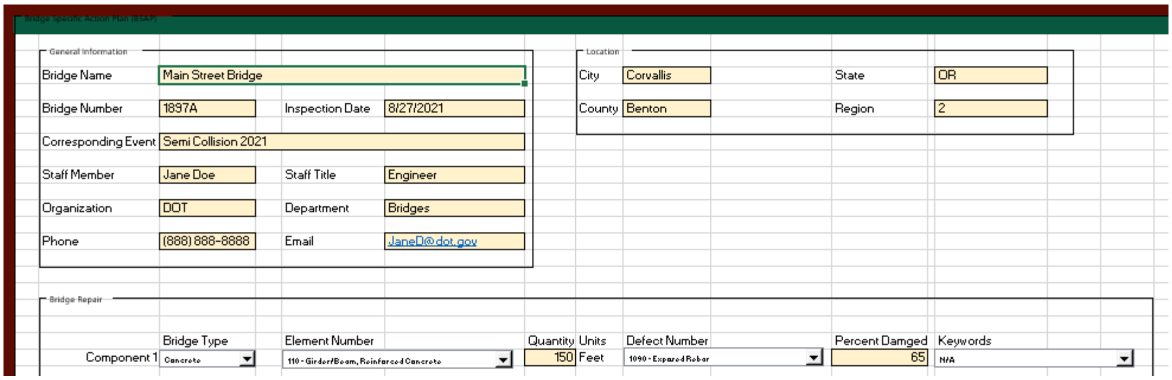
Figure 5-5. Hypothetical example of EEAP Output for Magnitude 6.8 Earthquake Page 2

5.4.3 Bridge Specific Action Plan

The Bridge Specific Action Plan (BSAP) provides users with a suggested action plan based on the observed damage to the bridge. The suggested action plan includes possible repair solutions. The observed damage inputs align with the MBEI elements and defects (AASHTO 2019). Key inputs include bridge type, element number, defect, and keywords (Figure 5-6). By default, BSAP is developed to assume that all listed defects are condition state 4 (*severe*). Repair methods for *minor* and *moderate* damage are not included within BSAP, as they are not typically addressed in emergency situations. However, users can customize BSAP to include repair solutions for lower condition states if desired. Additional condition states and customization for state-specific element numbers, defects, keywords, and repair options are outlined in the Developer's Guide to meet the needs of each user.

Figure 5-6. BSAP User Workflow

An example BSAP action plan input is shown in Figure 5-7, and the corresponding example output is shown in Figure 5-8 and Figure 5-9.



General Information

Bridge Name	Main Street Bridge		
Bridge Number	1897A	Inspection Date	8/27/2021
Corresponding Event	Semi Collision 2021		
Staff Member	Jane Doe	Staff Title	Engineer
Organization	DOT	Department	Bridges
Phone	(888) 888-8888	Email	JaneD@dot.gov

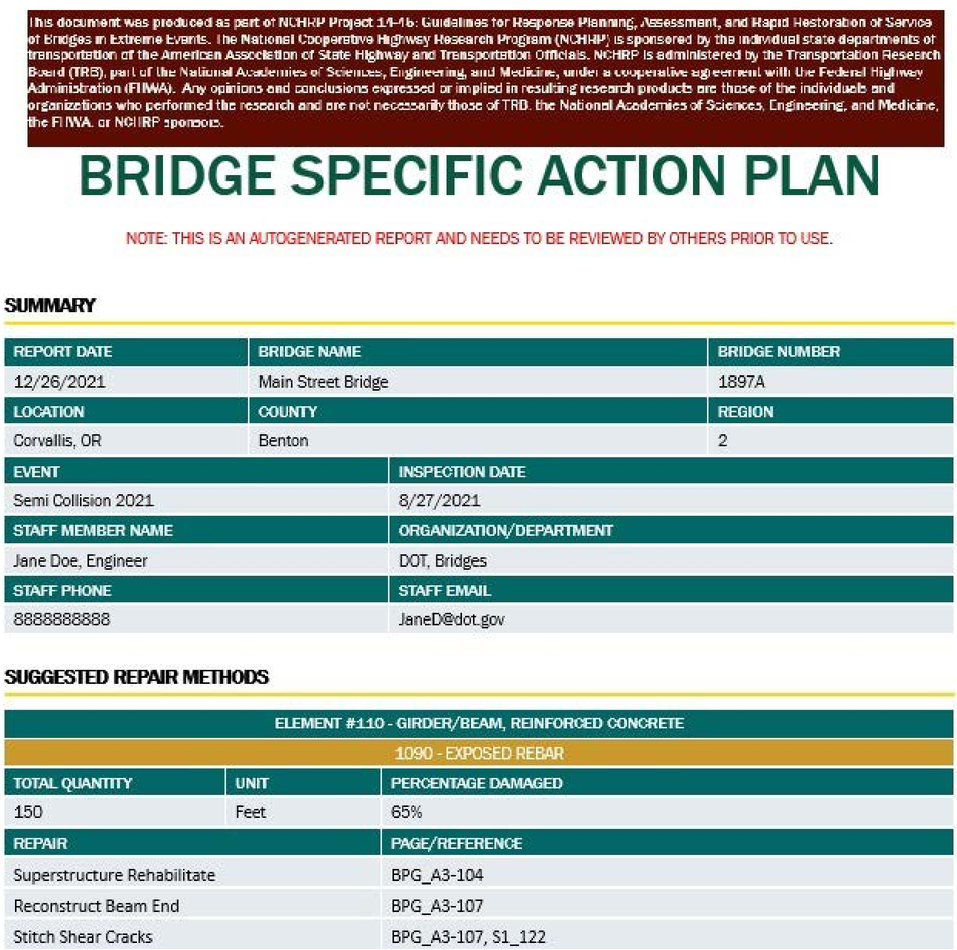
Location

City	Corvallis	State	OR
County	Benton	Region	2

Bridge Repair

	Bridge Type	Element Number	Quantity	Units	Defect Number	Percent Damged	Keywords
Component 1	Concrete	110 - Girder/Beam, Reinforced Concrete	150	Feet	1090 - Exposed Rebar	65	N/A

Figure 5-8. BSAP Example Inputs



This document was produced as part of NCHRP Project 14-46: Guidelines for Response Planning, Assessment, and Rapid Restoration of Service of Bridges in Extreme Events. The National Cooperative Highway Research Program (NCHRP) is sponsored by the individual state departments of transportation of the American Association of State Highway and Transportation Officials. NCHRP is administered by the Transportation Research Board (TRB), part of the National Academies of Sciences, Engineering, and Medicine, under a cooperative agreement with the Federal Highway Administration (FHWA). Any opinions and conclusions expressed or implied in resulting research products are those of the individuals and organizations who performed the research and are not necessarily those of TRB, the National Academies of Sciences, Engineering, and Medicine, the FHWA, or NCHRP sponsors.

BRIDGE SPECIFIC ACTION PLAN

NOTE: THIS IS AN AUTOGENERATED REPORT AND NEEDS TO BE REVIEWED BY OTHERS PRIOR TO USE.

SUMMARY

REPORT DATE	BRIDGE NAME	BRIDGE NUMBER
12/26/2021	Main Street Bridge	1897A
LOCATION	**COUNTY**	**REGION**
Corvallis, OR	Benton	2

EVENT	INSPECTION DATE
Semi Collision 2021	8/27/2021
STAFF MEMBER NAME	**ORGANIZATION/DEPARTMENT**
Jane Doe, Engineer	DOT, Bridges
STAFF PHONE	**STAFF EMAIL**
8888888888	JaneD@dot.gov

SUGGESTED REPAIR METHODS

ELEMENT #110 - GIRDER/BEAM, REINFORCED CONCRETE		
1090 - EXPOSED REBAR		
TOTAL QUANTITY	**UNIT**	**PERCENTAGE DAMAGED**
150	Feet	65%

REPAIR	PAGE/REFERENCE
Superstructure Rehabilitate	BPG_A3-104
Reconstruct Beam End	BPG_A3-107
Stitch Shear Cracks	BPG_A3-107, S1_122

Figure 5-7. BSAP Example Generated Output (Page 1)

POSSIBLE TEMPORARY SOLUTIONS

All projects are unique and have their own set of requirements. Some temporary solutions that may be helpful with the rapid restoration of this project include:

- Washington Department of Transpiration's *Rapid Repair Design of Temporary Support Systems for Bridges Damaged by Earthquakes in the State of Washington* (2001), see source S17 in the BSAP Library
- Caltrans *Trenching and Shoring Manual* (2011), see source S18 in the BSAP Library
- Caltrans *Falsework Manual* (2021), see source S19 in the BSAP Library
- Iowa DOT's *Emergency Response Manual for Over Height Collisions to Bridges*, see source S9 in the BSAP Library
- *NCHRP Report 280: Guidelines for Evaluation and Repair of Prestressed Concrete Bridge Members*, see source S13 in BSAP Library
- Proprietary Temporary Structure Options, see source S20 in the BSAP Library

SIGNATURES

Revised By	Print Name:	____________________	Date:	__________
	Signed Name:	____________________	Date:	__________
Approved By	Print Name:	____________________	Date:	__________
	Signed Name:	____________________	Date:	__________

DRAFT

Figure 5-9. BSAP Example Generated Output (page 2)

5.4.4 Case Studies Tool

The Case Study tool (CST) provides a sample of recent events that can serve as examples for State DOT-specific knowledge transfers and to share lessons learned with other state DOTs. The CST has two features: (1) to generate new case studies from an Excel and Word-based template, and (2) to review existing case studies (Figure 5-10). The CST is preloaded with 27 case studies and include a form to quickly generate additional case studies in the same format. The existing case studies are PDFs of Word documents, and the template case studies are Word documents that contains a brief overview of the emergency event, cost, assessment techniques, type of repairs, and key lessons learned with each project. The included case studies are based on the NCHRP 14-45 literature review and were collected from several state transportation agencies from across the United States. They represent a wide range of emergency event types, assessment techniques, and repair solutions adopted during extreme events from the recent past. Sample case studies are shown in Appendix C.

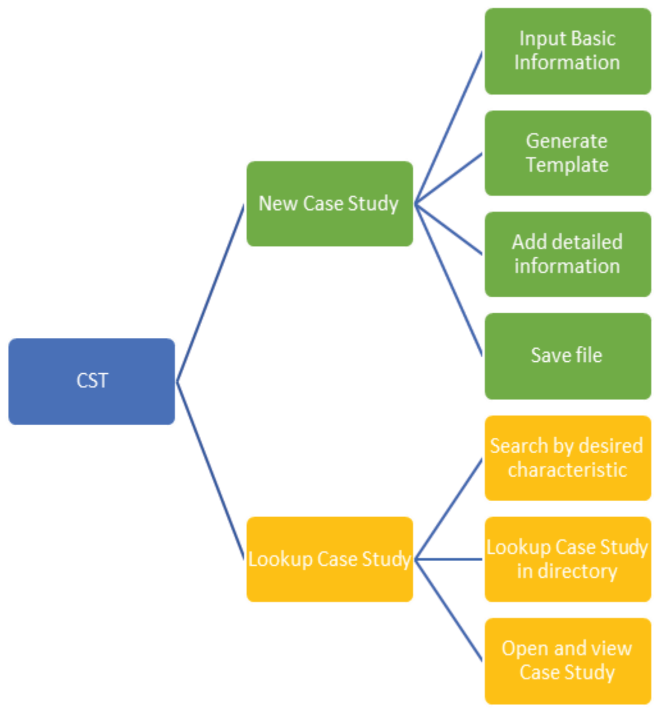


Figure 5-10. CST User Workflow

5.4.5 Status Form

The Status Form is a Word document to quickly capture and share information with stakeholders. The Status Form is designed to serve as a memo-style document to organize emergency response information. Users first upload agency identifier information, edit the templates, and then distribute the document to key stakeholders (Figure 5-11). This chart organizes each structure by name and location, with columns to indicate the levels of inspection and coding/marking the structure completed.

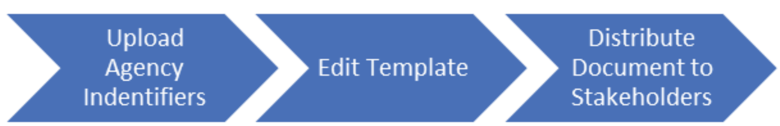


Figure 5-11. Status Form Workflow

The Status Form can progress throughout the emergency event response process if agencies choose. The form can be used up through repairs if it continues to be updated. If users have their own templates for these phases, they can be uploaded to BARRT and used in exchange for the "default" Status Form. An example of the produced Status Form is shown in Figure 5-12, Figure 5-13, and Figure 5-14.

DEPARTMENT OF TRANSPORTATION

Department of Transportation

DATE: 19 MAY 2019
TO: MAIN STAKEHOLDERS
FROM: JOHN SMITH, TRANSPORTATION DIRECTOR

SUBJECT: MAJOR EARTHQUAKE 2019 – UPDATE NO. 4

Greetings,
In response to the Major Earthquake that struck the western region on Friday, May 12th, the Department of Transportation has been diligently working to remove debris, completed structural assessments, and begun preparations for repairing damaged structures.

All highway bridges have completed the fast reconnaissance, preliminary damage assessments, and detailed damaged assessments. Structures with severe damage are currently undergoing extended investigations where applicable.

The North Crossing Bridge has now reopened after a temporary Bailey Bridge was installed. Further inspections will determine the best repair practices for this bridge. The Interstate 12 over the Yellow River Bridge remains closed until an extended investigation assessment is completed.

Inspection personnel from nearby states are starting to return home. We are confident our agency can wrap up any final assessments with our own staff and nearby consultants.

Another update is expected for next Tuesday, May 23rd.

Thank you for your continued support on our path to recovery.

John Smith, PE

UPDATE LOG

DATE	TIME	UPDATE
5/19/19	10am (EST)	North Crossing Bridge Reopened; out of state agents have returned home
5/15/19	12pm (ESt)	All detailed damage assessments have been completed. The Yellow River Bridge, Main Street Bridge, and Long Street Viaduct are opened with load restrictions.
5/13/19	9:30am (EST)	Fast reconnaissance and preliminary damage assessments have been completed. Meadows Creek, Jackson Ave, and National Hill Bridge are reopened.
5/12/19	3:15pm (EST)	Inspectors from nearby states are enroute to aid in fast reconnisance and preliminary damage assessments. All structures within a 25 miles radius are closed until assessments deem them safe.

CURRENT OPERATIONS

- All agency bridge inspectors are working on completing extended investigations on flagged infrastructure
- Orders have been placed for another Bailey Bridge from a nearby agency to temporarily replace the Interstate 12 Bridge
- Contracts for repair orders are being repaired for structures that are currently open

Figure 5-12. Example Status Form – Page 1

RESOURCES DEPLOYED

- Temporary Structures: (1) Bailey Bridge and (1) on the way
- Personnel: Bridge Inspection Teams 5- 9 completing all EIs. Teams 1-4 will trade off next Monday
- Equipment: (4) loaders and (2) rollers are in transit from Elliswood to prepare for approach repairs next week. All (12) inspector team kits are in the field

CONTRACTS

Consultants on the on-call contract have been notified of repairs that need to be completed. No contracts have been awarded, but are expected to go to bid next week.

Figure 5-13. Example Status Form – Page 2

STRUCTURE STATUS UPDATE

NAME	STRUCTURE NUMBER	LOCATION DESCRIPTION	STATUS	LOCATION	REGION	ASSESSMENTS COMPLETED				CODING/MARKING COMPLETED			TTC
						FR	PDA	DDA	EI	INSPECTED	LIMITED USE	UNSAFE	
North Crossing Bridge	01564A	Crosses Hilltop Road	Open	Lat 44.5635 N Long 123.2793 W	4	X	X	X				X	
Yellow River Bridge	300562	Second Street over the Yellow River	Restricted	Lat 44.5620 N Long 123.1865 W	4	X	X	X			X		X
Main Street Bridge	987698	Main Street over 14th Ave	Restricted	Lat 44.5589 N Long 123.5986 W	4	X	X	X			X		X
Long Street Viaduct	02564B	Long Street over Lucky Channel	Restricted	Lat 44.56486 N Long 123.6985 W	4	X	X	X			X		X
Meadows Creek Bridge	035697	Highway 45 over Meadows Creek	Open	Lat 44.51756 N Long 122.0264 W	3	X	X			X			
Jackson Ave Bridge	301235	Jackson Ave over Hillshire Road	Open	Lat 44.56306 N Long 123.2236 W	4	X	X			X			
National Hill Bridge	306897	Glencoe Street over Marshall Road	Open	Lat 44.6134 N Long 122.1596 W	3	X	X			X			
Interstate 12 Bridge	014458	Interstate 12 over the Yellow River	Closed	Lat 44.5699 N Long 123.5745 W	4	X	X	X				X	X
				Lat Long									
				Lat Long									
				Lat Long									

Figure 5-14. Example Status Form – Page 3

5.4.6 Contact Form

The Contact Form is an Excel spreadsheet for users to organize their important agency contacts to share internally and externally with other agencies. In future applications, this form is meant to be the inputs for a national database where State DOTs can upload their contact information to one location. Individual State DOTs are responsible for keeping their agency's contact information up to date.

Once users open the Contact Form workbook, they will browse the four main headings: general, primary call list, bridge groups, and management – to help find the job title of interest. If the agency has a different job title than what is listed, the title can be edited, or additional rows can be added. Contact information then be typed into the listed fields. From here, users can send the updated Contact Form to internal and external agency contacts as part of extreme event preparation.

A sample of the Contact Form is shown in Figure 5-15.

CONTACT FORM				
General:				
Structures Division (Main Number)	Phone #	(888) 999-0000	Name	
	Cell #			
	Email		Region/District	
Traffic Operations Center (TOC)	Phone #		Name	
	Cell #			
	Email		Region/District	
State Emergency Command Center	Phone #		Name	
	Cell #			
	Email		Region/District	
Region 1	Phone #		Name	
	Cell #			
	Email		Region/District	
Region 2	Phone #		Name	
	Cell #			
	Email		Region/District	
Region 3	Phone #		Name	
	Cell #			
	Email		Region/District	
Region 4	Phone #		Name	
	Cell #			
	Email		Region/District	
Region 5	Phone #		Name	
	Cell #			
	Email		Region/District	
Region 6	Phone #		Name	
	Cell #			
	Email		Region/District	
Region 7	Phone #		Name	
	Cell #			
	Email		Region/District	
Region 8	Phone #		Name	
	Cell #			
	Email		Region/District	
Seismology Station	Phone #		Name	
	Cell #			
	Email		Region/District	
FHWA Contact	Phone #		Name	
	Cell #			
	Email		Region/District	

Figure 5-15. Contact Form – General

Chapter 6: Summary and Recommended Research

This report provides guidelines for state DOTs for the response planning, assessment, and rapid restoration of service of bridge for extreme events. Workflows were developed to aid state DOTs through this process, and these procedures are easily adaptable to meet the needs of the situation at hand and depending on the maturity level of the State DOT agency.

To create an efficient workflow, as First You Plan approach is adopted, and emphasizes the pre-event planning phases. In this phase, response actions are planned out, and State DOT personnel is trained through mock scenarios to simulate actual extreme events. For emergency assessment, the response is divided into four stages: Fast Reconnaissance, Preliminary Damage Assessment, Detailed Damage Assessment, and Extended Investigation. Roles of State DOT personnel for each of the four stages is detailed, and the expected level of resources needed is also discussed. Based on the findings from the assessment phase, rapid restoration solutions can be selected and implemented to restore service to a pre-specified level. In some instances, temporary solutions may be the best option until permanent restorations can be completed.

The three phases of response planning, assessment, and rapid restoration are modeled from the National Disaster Recovery Framework , which focuses on pre-event planning, response, and recovery. The proposed procedures (which are detailed in the developed guide and accompanying tool) are organized into three phases of planning, assessment, and rapid restoration, and are mapped to the National Disaster Recovery Framework.

From this research, *NCHRP Research Report 1098*was developed to organize the procedures identified during the literature review of today's state of the art and state of practice, which include DOT manuals and guides, scientific research, and conference projects. State DOTs can select which section(s) of the guide are most relevant to their specific needs and adopt these procedures for their own departmental use. The accompanying implementation tool, the Bridge Assessment Rapid Restoration Tool (BARRT) was discussed in Chapter 6. BARRT is an interactive Microsoft PowerPoint that contains templates, examples, and forms state DOTs can use as is, or upload their own set of resources and use BARRT as a unifying storage platform.

The guide can be integrated into current policies through the installation of an innovation group, which consists of personnel from the State DOT agency who are responsible to maintaining and updating the infrastructure required (digital platforms, physical documentation, etc.). Funding for an innovation group can be sourced from the FHWA's Everyday Counts program, which aims to promote innovation in the transportation field.

Overall, this research equips state DOTs with the tools they need to successfully plan for and respond to extreme events. In the long run, state DOTs will save time, money, and resources by carefully planning for extreme events. This not only promotes fiscal responsibility, but also benefits the public by reducing the amount of time it takes for a full recovery. Recommendations for future research include implementation pilot applications of the guide and use of the tool, to streamline the tool and test the application of the various sections of the guide for assessment, planning, and rapid restoration of service.

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List of Acronyms and Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ADA	Americans with Disabilities Act
ADE	Agency-Developed Elements
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing Materials
ATA	American Trucking Association
BIRM	Bridge Inspectors Reference Manual
BME	Bridge Management Element
BPA	Bridge Preservation Actions Guide
CE	Chief Engineer
CS	Condition State
CTAA	Communication Transportation Association
DDA	Detailed Damaged Assessment
DDAI	Detailed Damaged Assessment Inspector
DHS	Department of Homeland Security
DOE	Department of Energy
EOC	Emergency Operations Center
EOP	Emergency Operations Plan
EI	Extended Investigation
EII	Extended Investigation Inspector
EMC	Emergency Management Coordinator
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
FO	Functionally Obsolete
FR	Fast Reconnaissance
GIS	Geographic Information System
ICS	Incident Command System
LRFD	Load Resistance and Factor Design
MBE	Manual for Bridge Evaluation
MBEI	Manual for Bridge Element Inspection
ME	Managing Engineer
MMI	Modified Mercalli Intensity
NIMS	National Incident Management System
NBI	National Bridge Inventory
NBE	National Bridge Element
NCHRP	National Cooperative Highway Research Program
NTSB	National Transportation Safety Board
PDA	Preliminary Damage Assessment
PDAR	Preliminary Damage Assessment Responder

SD	Structurally Deficient
SHM	Structural Health Monitoring
TIM	Traffic Incident Management
UAS	Unmanned Aircraft Systems
US DOT	United States Department of Transportation

Glossary

Key Word	Definition	Source
Approach	Approach pavements, slabs, wearing surfaces, pressure relief joints, embankments, and slope protection for embankments (MBEI elements 320-321).	Guide to Bridge Preservation Actions
Assessing	The process of evaluating a structure's condition through inspection and possible data analysis or modeling. This can be completed manually or through technological means.	NCHRP Research Report 833
Assessment Forms	The assessment forms cover bridges and culverts. These forms will be completed by Preliminary Damage Assessment responders in the field following an emergency event.	NCHRP Research Report 833
Basic Training	Training for all employees who will act as Preliminary Damage Assessment responders or perform Preliminary Damage Assessments after an emergency.	NCHRP Report 833
Bearing	Fixed and movable bearing devices (MBEI elements 310-316).	Guide to Bridge Preservation Actions
Bridge	23 CFR 650: "A structure including supports erected over a depression or an obstruction, such as water, highway, or railway, and having a track or passageway for carrying traffic or other moving loads, and having an opening measured along the center of the roadway of more than 20 feet between under copings of abutments or spring lines of arches, or extreme ends of openings for multiple boxes; it may also include multiple pipes, where the clear distance between openings is less than half of the smaller contiguous opening."	Guide to Bridge Preservation Actions
Bridge Owner	The responsible party for a bridge's maintenance, rehabilitation, and replacement. The bridge owner is typically a local, state, or federal transportation agency.	
Capacity	Limits to volume, size, or weight of traffic that a bridge can carry.	Guide to Bridge Preservation Actions

Key Word	Definition	Source
Channel	The waterway below a bridge or at a culvert plus banks, bank protection, protection at substructures in water, stream diverters, channel cross section, and channel profile.	Guide to Bridge Preservation Actions
Chief Engineer (CE)	This role is reserved for the engineer who will coordinate specialty inspectors including structural, geotechnical, hydrological, mechanical, and materials.	NCHRP Research Report 833
Coding	The process of using shortened notation or series of code to indicate the status of a structure, its components and elements, and other parameters associated with it.	NCHRP Research Report 833
Component	1. A keyword of the object of action. Components are approach, bearing, bridges, channel, culvert, deck, drain, joint, railing, substructure, and superstructure. 2. A group of related bridge elements. NBI elements: deck, superstructure, substructure, channel, and culvert.	Guide to Bridge Preservation Actions
Condition	The presence, severity, and extent of defects in bridges, components, or elements.	Guide to Bridge Preservation Actions
Condition Rating	An overall assessment of the physical condition of a deck, superstructures, substructure, or culvert. NBI general condition rating range from 0 (failed) to 9 (excellent).	Guide to Bridge Preservation Actions
Condition State (CS)	A defined condition for an element of a bridge. Also, the integer value used in bridge inspection reports to identify the severity of defect.	Guide to Bridge Preservation Actions
Condition, fair	General condition rating equal to 5 or 6, or element condition state equal to 2.	Guide to Bridge Preservation Actions
Condition, good	General condition rating equal to 7, 8, or 9, or element condition state equal to 1.	Guide to Bridge Preservation Actions
Condition, poor	General condition rating equal to 4, 3, 2, 1, or 0, or element condition state equal to 3.	Guide to Bridge Preservation Actions
Condition, severe	Element condition state equal to 4.	Guide to Bridge Preservation Actions
Culvert	A curved or rectangular buried conduit for conveyance of water, vehicles, utilities, or pedestrians (MBEI elements 240-245).	Guide to Bridge Preservation Actions

Key Word	Definition	Source
Deck	Structural decks, slabs, wearing surfaces, and waterproofing membranes (MBEI elements 12-65 and 510).	Guide to Bridge Preservation Actions
Defect	As described by the MBEI, defects help assess the overall condition of a bridge. Defects are specific to each element.	
Detailed Damage Assessment	Provides an evaluation of structural damage and decisions on use restriction after Preliminary Damage Assessment.	NCHRP ResearchReport 833
Detailed Damage Assessment Inspector (DDAI)	These include structural inspection teams with significant background and experience for detailed inspection of structures.	NCHRP Report 833
Drain	Grates, scuppers, downspouts, pipes, supports, outlets, and splash blocks.	Guide to Bridge Preservation Actions
Durability	A qualitative assessment of the resistance of bridges and components to deterioration. A bridge has adequate durability if its materials, design details, and devices meet current standards, or if its materials, design details, and devices are obsolete but have adequate resistance to deterioration.	Guide to Bridge Preservation Actions
Elements, Bridge	A national bridge element (NBE) or bridge management element (BME), as defined in MBEI, plus agency-developed elements (ADE).	Guide to Bridge Preservation Actions
Element Damage Rating	These damage levels (none, minor, moderate, or severe) are specific to basic structure elements and are used to provide information for repair, prioritization, and subsequent assessment procedures.	NCHRP Research Report 833
Emergency Data Coordinator	Individual who is responsible for coordinating all the digital data, ensuring its quality, and providing that data in a form that is more useful for response.	NCHRP Research Report 833
Emergency Event	An event that is unplanned and that requires immediate attention from first responders and State DOTs to secure the scene, protect the public, and assess the impacted structure. This could include hurricanes/storm surge, tsunamis, earthquakes, fires, collisions, floods, and man-made events.	

Key Word	Definition	Source
Emergency Management Coordinator	Individual who will have responsibility for all coordination and communication in case of an emergency across the entire transportation agency.	NCHRP Research Report 833
Emergency Operations Plan	Emergency operations plans detail the scope of preparedness and emergency management activities that are required.	NCHRP Research Report 833
Evaluation, Structural	From FHWA A combined rating for condition and load rating as a function of average daily traffic (ADT), NBI Item 67.	Guide to Bridge Preservation Actions
Extended Investigation	An in-depth inspection that requires specialized technologies. This stage is typically performed after an UNSAFE rating from the Detailed Damage Assessment stage.	NCHRP Research Report 833
Extended Investigation Inspector (EII)	These inspectors should be specialists (e.g., structural, geotechnical, hydrological, mechanical, materials, etc.) who will provide specific recommendations on necessary restrictions and/or repair, detailed damage analysis, and approximate cost estimate for remedial work.	NCHRP Research Report 833
Extreme Event	Emergency events that are rare in frequency and high in severity; some events that are considered extreme in one region may not be extreme in another. This definition is highly depended on time, location, and consequences of the damages observed.	NCHRP Synthesis 497
Fast Reconnaissance	Provides a global perspective to establish the extent of the damaged region immediately following an emergency event.	NCHRP Research Report 833
Fast Reconnaissance Coordinator	This individual oversees monitoring and organizing Fast Reconnaissance methods and reporting these findings to best determine the appropriate response levels.	NCHRP Research Report 833
Federal-Aid Highway	From 23 USC 101, definitions, and declaration of policy A public highway eligible for assistance under Title 23 USC, other than a highway functionally classified as a local road or rural minor collector.	Guide to Bridge Preservation Actions
First Responders	Emergency personnel with specialized training that is first to respond to an incident, including but not limited to, police, fire fighters, EMTs, and incidence response.	

Key Word	Definition	Source
Functionally Obsolete (FO)	From FHWA A classification given to a bridge that has an appraisal rating of 3 or less for Item 68 (deck geometry), Item 69 (under clearances), or Item 72 (approach roadway alignment), or that has an appraisal rating of 3 for Item 67 (structural condition) or Item 71 (waterway adequacy). FO in general is a function of the geometries (broad roadway width, load-carrying capacity, clearances, approach roadway alignment) of the bridge in relation to the geometries required by current design standards. The magnitude of such deficiencies determines whether a bridge is classified as "functionally obsolete".	Guide to Bridge Preservation Actions
Geographic Information System (GIS)	A spatial system to manage, create, and assess data.	
Incident Command System (ICS)	A standardized method to establish command and maintain control of an emergency event. The system creates order among a multitude of departments, agencies, and organizations by assigning roles and responsibilities and establishing a chain of command.	
INSPECTED	This classification utilizes a green color and indicates that no apparent damage was found, and the structure can function without further investigation.	NCHRP Research Report 833
Inspection Routes	This is the list of bridges that a Preliminary Damage Assessment responder will evaluate following an emergency event.	NCHRP Research Report 833
Inspector	Knowledgeable individual within an agency that has experience performing routine inspection of highway structures.	NCHRP Research Report 833
Joint	Fixed and moveable joints in decks.	
LIMITED USE	This classification utilizes a yellow color and indicates that minor to moderate damage conditions are observed or believed to be present. The structure requires further evaluation but can still be used for restricted traffic.	NCHRP Research Report 833
Logistics Coordinator	Responsible for coordinating logistics (travel, housing, hospitalization) support for inspectors, particularly if staff is brought in from outside the state.	NCHRP Research Report 833

Key Word	Definition	Source
Managing Engineer (ME)	The key lead for making all structural assessment decisions regarding bridges.	NCHRP Research Report 833
Marking	The process of applying an identifiable mark to the structure to inform others of its condition. This can be done physically or digitally. This physical marking of a structure is sometimes referred to as “posting”.	NCHRP Research Report 833
Minor Damage	The element shows cosmetic or non-structural damage.	NCHRP Research Report 833
Moderate Damage	The element has experienced structural or geotechnical damage.	NCHRP Research Report 833
Modified Mercalli Intensity (MMI)	Measures intensity of an earthquake based on observed damages.	USGS
National Bridge Inventory (NBI)	The reports, system of reporting, and format from data on bridges on public roads required under 23 USC 144 and defined in 243 CFR 650.	Guide to Bridge Preservation Actions
National Incident Management System (NIMS)	National framework that guides agencies and organizations through emergency event response. The use of NIMS helps reduce traffic disruption, increase safety of first responders, create efficient on-scene management, and keeps the public informed of the changing situation.	FEMA 2017
No Collapse	This classification is an optional outcome of a Fast Reconnaissance and indicates that the structure has been observed from a distance or using remote sensing techniques and is not partially or fully collapsed.	NCHRP Research Report 833
Overlay	Concrete or polymer overlay. Asphalt wearing surface with or without waterproofing membrane (MBEI element 510).	Guide to Bridge Preservation Actions
Owner	The entity that maintains ownership of the bridge or culvert. The owner may not retain responsibility maintenance and repair through contracts or other agreements. The owner is often the governing transportation agency.	
Preliminary Damage Assessment	An assessment performed for each structure immediately after an event, preferably within hours, to provide information on the status of the structure and to determine whether subsequent assessment stages will be needed.	NCHRP Research Report 833

Key Word	Definition	Source
Preliminary Damage Assessment Responder (PDAR)	An individual who will perform Preliminary Damage Assessment evaluations following an emergency event.	NCHRP Research Report 833
Preservation	A program of actions to keep bridges in fair or good condition and to extend service life.	Guide to Bridge Preservation Actions
Preservation Action	Work to maintain, protect, or repair major components of bridges, plus work to maintain, repair, retrofit, or replace other components of bridges.	Guide to Bridge Preservation Actions
Priority Level	Priority levels are given to highway routes that are of critical importance to the transportation network. These include lifeline routes and other routes that link important infrastructure.	NCHRP Research Report 833
Radius of Concern	An approximate radius that captures the region threatened or impacted by an extreme event. This radius is typically centered at the location of the extreme event, but may be shifted to center over a larger metropolis or areas of greater risk.	
Railing	Parapets and railings along decks. Guardrail along approaches (MBEI elements 330-334).	Guide to Bridge Preservation Actions
Rehabilitate	Repair and/or replacement of portions of bridges to restore fair or good condition and to restore original load capacity.	Guide to Bridge Preservation Actions
Rehabilitation, Bridge	From 23 CFR 650 Major work required to restore the structural integrity of a bridge as well as work necessary to correct major safety defects.	Guide to Bridge Preservation Actions
Repair	Work to correct defects in bridge components or elements. Replacement of a portion of a component or element is a Repair.	Guide to Bridge Preservation Actions
Replace	Compete provision of new bridge components or elements. Work can be replaced-in-line or replaced with improved design, materials, or capacity.	Guide to Bridge Preservation Actions
Replacement, Bridge	From 23 CFR 650 Total replacement of a structurally deficient or functionally obsolete bridge with a new facility constructed in the same general traffic corridor.	Guide to Bridge Preservation Actions
Response Levels	Relates to the immediacy of the response, the level of resources, and the effort that will be put into a response during an emergency event.	NCHRP Research Report 833

Key Word	Definition	Source
Restoration of Service	Returning a bridge to a functioning level of service that is defined by the State DOT. This may be defined as partial capacity or restricted access, partial opening, or full opening.	
Retrofit	Modification of bridge components or elements to improve durability, function, or capacity.	Guide to Bridge Preservation Actions
Robustness	An assessment of vulnerability of a bridge to sudden failure of bridges in service. Vulnerabilities to fatigue, fracture, scour, overload, earthquake, and threat vulnerability are considered. Bridges that meet current agency design standards are robust.	Guide to Bridge Preservation Actions
Seal	Application of materials to provide waterproofing to surfaces. Application of materials to seal cracks in concrete.	Guide to Bridge Preservation Actions
Severe Damage	The element is damaged where it cannot function properly	NCHRP Research Report 833
Specialized Training	Training for emergency management coordinators, emergency data coordinators, chief engineers, Detailed Damage Assessment inspectors, and Extended Investigation inspectors.	NCHRP Research Report 833
Structurally Deficient (SD)	From 23 CFR 490 A classification given to a bridge which has any components in poor or worse condition. When the lowest rating of the 3 NBI items for a bridge is 4, 3, 2, 1, or 0, the bridge will be classified as poor. When the rating of an NBI item for a culvert is 4, 3, 2, 1, or 0, the culvert will be classified as poor. From FHWA Bridges are considered “structurally deficient” if (1) significant load-carrying elements are found to be in poor or worse-than-poor condition due to deterioration or damage, or (2) the adequacy of the waterway opening the bridge provides is determined to be insufficient to the point of causing intolerable traffic interruptions due to high water. That a bridge is structurally deficient does not mean it is unsafe.	Guide to Bridge Preservation Actions
Substructure	Abutments, footings, pier walls, pier columns, and pier caps (MBEI elements 202-236, 515, 520, 521).	Guide to Bridge Preservation Actions

Key Word	Definition	Source
Superstructure	Beams, girders, stringers, arches, cables, and trusses (MBEI elements 102-162).	Guide to Bridge Preservation Actions
UNSAFE	This classification utilizes a red color and indicates the structure has experienced severe damage or collapsed and cannot function under traffic loads.	NCHRP Research Report 833

Appendix A: Questionnaire

NCHRP 14-45 Bridge Engineers Questionnaire

Start of Block: Welcome

Welcome As part of NCHRP 14-45 “**Response Planning, Assessment, and Rapid Restoration of Service of Bridges in Extreme Events**,” the Project Team is charged with acquiring information related to the development of NCHRP 14-45 Guidelines that support this project.

These Guidelines are intended to complement, not replace, the National Bridge Inspection Standards (NBIS) and its requirements for proper inspection techniques. The Guidelines will play a large role in disaster situations that require emergency assessment and rapid restoration of bridges and culverts, providing standard operating procedures for transportation agencies to have at their disposal to quickly prioritize, inspect, and repair bridges to limit disruption to social and economic activities, and aid in disaster relief at a community or regional scale.

This questionnaire is intended to take you approximately 30 minutes to complete. Thank you in advance for your time and thoughtful consideration.

For purposes of this questionnaire, the following definitions are intended:
Assessment – Evaluation of a bridge or culvert’s current condition through onsite inspection and possibly data analysis or modeling. This can be completed manually or through technological means.
Emergency Inspection – The process of examining a bridge or culvert to determine if it suffers any damage due to an extreme event. This includes looking for a reduction of capacity (due to element- or system-level damage), necessity to close the bridge until emergency repairs are completed and identifying any changes to the bridge’s overall condition. This usually takes place on site; but it can also be done remotely with technological means or supplemented with analyses.
Extreme events – These can include earthquake, tsunami, hurricanes, high winds, storm surge, flooding, tornado, fire, collision-related traffic accidents, and man-made hazards that cause a bridge or culvert to go out of full service and cause major disruption to the transportation system.
Man-Made Hazards – Include events caused by human error, such as design flaw or improper construction, or by targeted attacks.
Rapid Restoration of Bridges or Culverts – The process of quickly repairing, replacing, or setting up a temporary structure in response to bridge or culvert damage caused by an extreme event. These restorations are usually time-sensitive and may require complete or partial closure of the bridge or culvert until construction is complete.

Response Planning – Preparation for a potential extreme event, including training, securing construction materials, setting in place emergency bidding protocols, and organizing management to be able to quickly adapt to the dynamic nature of an extreme event.
Routine Inspection – The process of examining a bridge or culvert to determine its condition on a regular basis. This process is typically completed manually on site, but some parts can be done via technological means. The most common example would be a routine inspection via National Bridge Inspection Standards.
Routine Repairs – Repairs that are cyclical, such as cleaning deck drains or resealing bridge joints, and are performed on a scheduled basis. These are often smaller repairs that do not require a great amount of resources, such as equipment or workers.
Scour – Removal of waterway sediment around bridge piers, bridge abutments, or culvert linings. Leads to erosion and undermining of the supports which can cause structure failure.
Scour Event – An event where heavy scour occurs. Typically arises during a flood but can occur over time due to normal waterway conditions.

If you wish to stop the questionnaire and continue later, you may do so by saving the form. You can do so only with the same computer and browser and completed fields will only be saved up to one week. Please only use the controls at the bottom of the questionnaire page to advance or return to the previous page. Your browser's back and forward buttons will not work with this questionnaire. Please note that not all questions will be displayed based on your selections. There are 21 questions in total.

We understand that you receive numerous questionnaires and they require your valuable time. We thank you in advance for your response and investing your time. Your organization and others will benefit from your input. A copy of the results will be made available once the results have been received, compiled, and approved by the NCHRP.

Kind Regards,
Dr. Andre Barbosa
Associate Professor | Oregon State University

End of Block: Welcome

Start of Block: General Information (Question 1)

Q1 Contact Information

- ☐ Position/Title ____
- ☐ Division/Department ____
- ☐ Agency ____
- ☐ Name ____
- ☐ Email ____
- ☐ Phone Number (XXX) XXX-XXXX ____

End of Block: General Information (Question 1)

Start of Block: Emergency Preparedness (Questions 2-4)

Q2 Does your agency have documented procedures related to the planning, assessment, and restoration of bridges and/or culverts in extreme events?

	0 (no procedures)	1 (informal procedures in place with minimal documentation)	2 (procedures in place with documentation but need more development)	3 (detailed procedures in place with documentation)	4 (detailed procedures in place with documentation and training)
Planning	☐	☐	☐	☐	☐
Assessment	☐	☐	☐	☐	☐
Restoration	☐	☐	☐	☐	☐

... Please send an email to nchrp14.45@gmail.com with documents pertaining to **response planning.**

... Please send an email to nchrp14.45@gmail.com with documents pertaining to **assessment**.

... Please send an email to nchrp14.45@gmail.com with documents pertaining to **rapid restoration**.

Q3 Does your agency have a Plan of Action (POA) for scour critical bridges and/or culverts?

- o Yes
- o No

... Please send all document(s) pertaining to the example to nchrp14.45@gmail.com

... Please comment on this example:

____
____
____
____
____

Q4 What level of training does your agency organize for assessing bridges and culverts following extreme events?

- ☐ None
- ☐ Every 5 years
- ☐ Every few years
- ☐ Annually
- ☐ A few times a year
- ☐ Monthly or more

... What type(s) of events does your agency train for?

- ☐ Earthquake
- ☐ Tsunami

- ☐ Flood
- ☐ Hurricane
- ☐ Fire
- ☐ Collision
- ☐ Scour
- ☐ Tornado (including debris impact)
- ☐ Other (please specify) ____

End of Block: Emergency Preparedness (Questions 2-4)

Start of Block: Emergency Assessment (Questions 5 - 8)

Q5 How likely is your agency to use the following technologies for **emergency** bridge/culvert inspection

	Extremely unlikely	Somewhat unlikely	Neither likely nor unlikely	Somewhat likely	Extremely likely
Smart Devices with a specific app (e.g., Fulcrum)	☐	☐	☐	☐	☐
Smart Devices without a specific app	☐	☐	☐	☐	☐
Unmanned aircraft systems/drones	☐	☐	☐	☐	☐
Lidar	☐	☐	☐	☐	☐
Survey-Grade GPS/GNSS	☐	☐	☐	☐	☐
Autonomous boats or underwater vessels	☐	☐	☐	☐	☐
Elevation detection device to measure water depth	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐
Other	☐	☐	☐	☐	☐

Q6 Does your agency have documentation that details how your agency ranks structures before/during/after emergency events?

- ☐ Yes
- ☐ No
- ☐ Not Sure

... How does your agency prioritize emergency bridge inspection after a disaster? Is there a specific methodology or rating system used?

____
____
____
____
____

... Please provide file(s) of supporting documentation that details how your agency ranks structures before/during/after emergency events, if available, by sending an email to nchrp14.45@gmail.com

Q7 What impediments to performing emergency bridge inspections has your agency encountered? Rank each of these factors, with 1 being the biggest obstacle:

______ Prioritizing structures to inspect
______ Contracting qualified contractors
______ Lack of technical expertise
______ Lack of in-house inspectors
______ Lack of guidelines
______ Lack of training
______ Other
______ Other
______ Other

Q8 Has your agency implemented practices or products of NCHRP Guidelines (NCHRP Report 833)for Assessing, Coding & Marking of Highway Structures in Emergency Situations?

- ☐ Yes, have implemented some of the results into current agency practices
- ☐ Not yet, but are considering implementing results
- ☐ No, not currently using, but have heard of the report
- ☐ Have not heard of it

... Please provide any comments on these NCHRP 833 guidelines or on any other guidelines currently used by your agency for Assessing, Coding, Marking of Highway Structures in Emergency Situations.

____
____
____
____
____

End of Block: Emergency Assessment (Questions 5 - 8)

Start of Block: Repairs (Questions 9 - 15)

Q9 Many agencies use a mix of in-house staffing and internal resources along with external engineering consultants and contractors for routine repair projects and rapid restoration. **Please provide your best estimate for the percentage of external work.**

	% External
Routine Repair	☐
Design & Engineering Documents	☐
Performing Repairs or Construction Work	☐
Rapid Restoration	☐
Design & Engineering Documents	☐
Performing Repairs or Construction Work	☐

Q10 Please rate the following factors on the importance they carry for your agency when deciding on a repair method for **routine repairs**

	Not considered	Low	Medium	High
Cost	o	o	o	o
Time	o	o	o	o
Ease of Maintenance	o	o	o	o
Limiting Service Interruption	o	o	o	o
Load Capacity	o	o	o	o
Service Life	o	o	o	o
Aesthetics	o	o	o	o

Q11 Please rate the following factors on the importance they carry for your agency when deciding on a repair method for **rapid restoration**

	Not considered	Low	Medium	High
Cost	o	o	o	o
Time	o	o	o	o
Ease of Maintenance	o	o	o	o
Limiting Service Interruption	o	o	o	o

Load Capacity	o	o	o	o
Service Life	o	o	o	o
Aesthetics				

Q12 Please rate the likelihood of your agency employing these rapid restoration techniques/procedures:

	Extremely unlikely	Somewhat unlikely	Neither likely nor unlikely	Somewhat likely	Extremely likely	Already implementing
Common construction techniques	o	o	o	o	o	o
Portable prefabricated solutions, like a Bailey bridge	o	o	o	o	o	o
Accelerated Bridge Construction	o	o	o	o	o	o
Accelerated version of traditional Design-Bid-Build project delivery	o	o	o	o	o	o
Delegation of authority to waive routine contracting procedures	o	o	o	o	o	o
Indefinite delivery/indefinite quantity contracts in anticipation of the need for emergency services	o	o	o	o	o	o
Preliminary consultant contract to	o	o	o	o	o	o

quantify the scope of emergency design and construction work						
Emergency procurement procedures that are based on the routine procedures but with a higher priority	o	o	o	o	o	o
Standing list of prequalified designers and contractors	o	o	o	o	o	o
Standard shoring details to stabilize or support bridges after extreme events	o	o	o	o	o	o
Other	o	o	o	o	o	o
Other	o	o	o	o	o	o
Other	o	o	o	o	o	o

... Please provide the link(s) to any documentation available regarding the selected techniques/practices by sending an email to nchrp14.45@gmail.com

Q13 What impediments to rapid restoration of service has your agency encountered? Rank each of these factors, with 1 being the biggest obstacle:

_______ Procurement of materials
_______ Contracting qualified contractors
_______ Lack of technical expertise
_______ Lack of guidelines
_______ Lack of training
_______ Other
_______ Other
_______ Other

Q14 Delays to initiation of repairs can be caused by “impending factors” – inspection progress, access to funding, engineering review or re-design, contractor mobilization, and permitting. Rank each of these factors, with 1 being the most important, in the order of which can cause the most delays:

______ Inspection progress
______ Access to funding
______ Engineering review or re-design
______ Contractor mobilization
______ Permitting

Q15 What strategies does your agency consider for long-lead items necessary for rapid restoration

- ☐ Prefabricated components stockpiled
- ☐ Stockpiled materials
- ☐ Specialized pre-arrangements with vendors
- ☐ Temporary solution until long-lead item available
- ☐ Other (please specify) ____
- ☐ Other (please specify) ____
- ☐ Other (please specify) ____

End of Block: Repairs (Questions 9 - 15)

Start of Block: Case Studies (Question 16)

Q16 Does your agency have an interesting and useful example of a rapid assessment and/or restoration after a major event? An example could be the use of Accelerated Bridge Construction to repair a collision with an overheight vehicle or a new bidding procedure to speed up construction after a hurricane.

- o Yes
- o Maybe
- o No

... What type of disaster was it?

- ☐ Earthquake
- ☐ Tsunami
- ☐ Floods
- ☐ Hurricane
- ☐ Fire
- ☐ Collision
- ☐ Scour
- ☐ Tornado (including debris impact)
- ☐ Other ____

... What locations were affected?

____
____
____
____
____

... Please describe the situation:

____

____
____
____
____

... How many bridges were damaged from this event?
____

... What was the total cost (or estimate) of the repairs?
____

... How long did it take to restore partial capacity (i.e., reopening one lane to traffic)? Full Capacity?

	Days	**Weeks**	**Months**	**Years**
Partial	☐	☐	☐	☐
Full	☐	☐	☐	☐

... What assessment techniques were used?
- ☐ Visual Inspection
- ☐ Non-Destructive Testing
- ☐ Smart Devices
- ☐ Digital Cameras
- ☐ Unmanned aircraft systems/drones
- ☐ lidar
- ☐ Survey-Grade GPS/GNSS
- ☐ Other ____

... What repair/rapid restoration techniques were used (Accelerated Bridge Construction, etc.)?
____
____
____
____
____

... Who should we contact for more information about this event (if known)?
Name ____
Title ____
Email Address ____
Phone Number (XXX) XXX-XXXX ____
Other ____

... Can we follow up with your agency for additional examples?
- ☐ Yes (please briefly describe the other examples)

☐ No

End of Block: Case Studies (Question 16)

Start of Block: Policy and Procurement (Question 17)

Q17 Agencies tend to use different contracting procedures depending on the project and other constraints for **routine repairs**. Please rank on the likelihood of your organization using the listed contracting types and methods by clicking and dragging each item (1 = most likely).

______ Traditional Design/Bid/Let/Construction
______ Accelerated Bridge Construction (ABC)
______ Design-Build Agreements
______ A+B Bidding (work + public impact costs)
______ On-Call/Standby Contracts
______ Indefinite Delivery/Indefinite Quantity Contracts
______ Maintenance Crews
______ Incentives or Disincentives
______ Emergency Procurement Procedures
______ Other

... Agencies tend to use different contracting procedures depending on the project and other constraints for **rapid restoration**. Please rank on the likelihood of your organization using the listed contracting types and methods by clicking and dragging each item (1 = most likely).

______ Traditional Design/Bid/Let/Construction
______ Accelerated Bridge Construction (ABC)
______ Design-Build Agreements
______ A+B Bidding (work + public impact costs)
______ On-Call/Standby Contracts
______ Indefinite Delivery/Indefinite Quantity Contracts
______ Maintenance Crews
______ Incentives or Disincentives
______ Emergency Procurement Procedures
______ Other

End of Block: Policy and Procurement (Question 17)

Start of Block: Communications (Questions 18 - 19)

Q18 Does your agency use or monitor the following technologies to gather information or communicate with the public regarding emergency events, closures, or construction delays?

	News Broadcasting	Website	Faceboo k	Instagram	Twitte r	Other	None
Crowdsourcing/ information gathering	☐	☐	☐	☐	☐	☐	☐
Communicate Closures/	☐	☐	☐	☐	☐	☐	☐

construction delays	

... How does your agency organize and communicate with other decision makers (e.g., transportation network) for rapid restoration of structures?

____
____
____
____
____

Q19 Does your agency use specialized or custom tools (i.e., software, apps, or process flowchart) for **response planning** of service of bridges in extreme events?

- ☐ Yes (please describe this tool and what additional features your agency would benefit from in this tool) ____
- ☐ No (please describe what would you like to see in such a tool) ____

... Does your agency use specialized or custom tools (i.e., software, apps, or process flowchart) for **assessment** of service of bridges in extreme events?

- ☐ Yes (please describe this tool and what additional features your agency would benefit from in this tool) ____
- ☐ No (please describe what would you like to see in such a tool) ____

... Does your agency use specialized or custom tools (i.e., software, apps, or process flowchart) for **rapid restoration** of service of bridges in extreme events?

- ☐ Yes (please describe this tool and what additional features your agency would benefit from in this tool) ____
- ☐ No (please describe what would you like to see in such a tool) ____

End of Block: Communications (Questions 18 - 19)

Start of Block: Conclusion (Questions 20 - 21)

Q20 Please rate your agency on its ability to prepare, assess, and respond to an extreme event.

	Not prepared	Somewhat able	Could get by if needed with current practices	Fairly Able	Well-prepared
Prepare for an extreme event	☐	☐	☐	☐	☐
Prioritize inspections	☐	☐	☐	☐	☐
Prioritize repairs considering	☐	☐	☐	☐	☐

the available budget					
Access emergency funding	☐	☐	☐	☐	☐
Contracting	☐	☐	☐	☐	☐
Construction	☐	☐	☐	☐	☐

Q21 Does your agency have any suggestions for future training to help prepare for an extreme event? If so, please explain.

____
____
____
____
____

End of Block: Conclusion (Questions 20 - 21)

Start of Block: End

End
Thank you for completing this questionnaire. We understand this requires significant time and effort on your part and appreciate your contribution to this research! Your feedback will be very helpful to guide this research and develop products that will be useful to your agency.

Sincerely,
Dr. Andre Barbosa and the Research Team

End of Block: End

Appendix B: Questionnaire Summary

B.1. Introduction

A questionnaire was administered to state bridge engineers from fifty-one departments of transportation (DOTs) across the United States and Washington D.C. from November 2020 to January 2021. Forty-six of the fifty-one DOTs responded (Figure B-1). The primary goals of this questionnaire were to learn about the transportation agencies' current practices and procedures, to identify areas of possible improvement, and to gather information about potential case studies. The questionnaire focused on the following sections:

- Emergency Preparedness
- Emergency Assessment
- Repairs
- Case Studies
- Policy and Procurement
- Communications
- General Conclusions

The following sections detail the results and overall conclusions of the administered questionnaire.

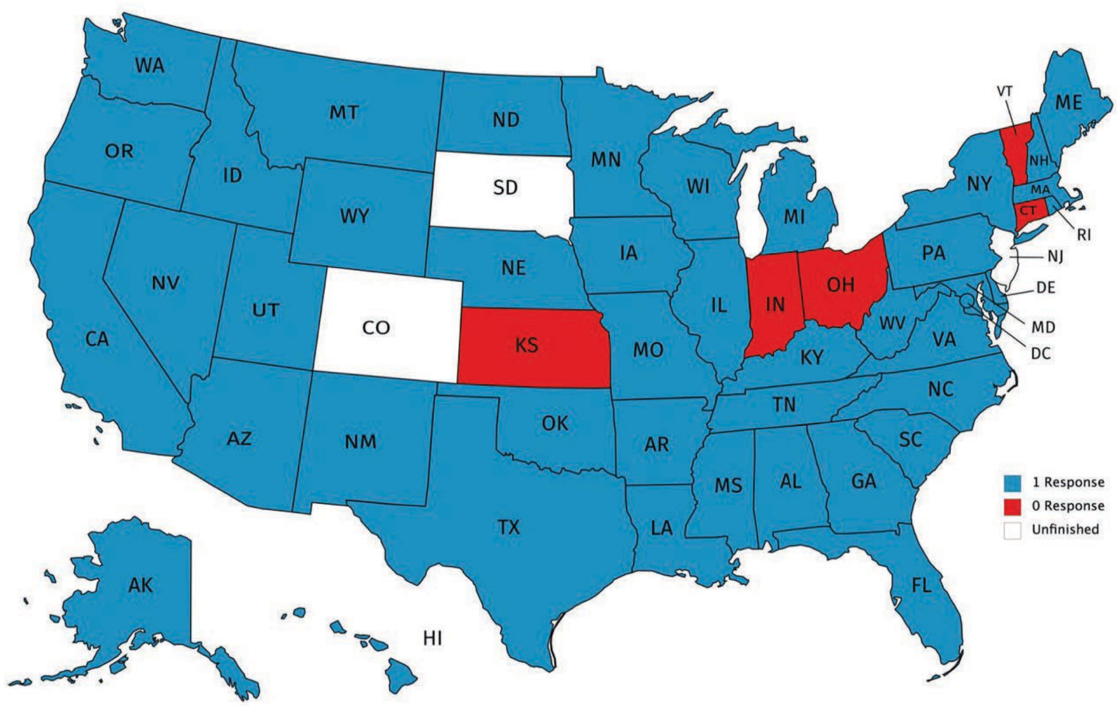


Figure B-1. Total DOT Respondents

B.2. Results

B.2.1 Agency Information

Basic information regarding the position/title of the respondents and their departments were captured at the beginning of the questionnaire. Most respondents were members of their respective state's bridge/highway structures departments, and a few were from other departments such as maintenance, design, development, or operations. Respondents' job titles consisted of a mix of bridge engineers, managers, and inspectors (Figure B-2).

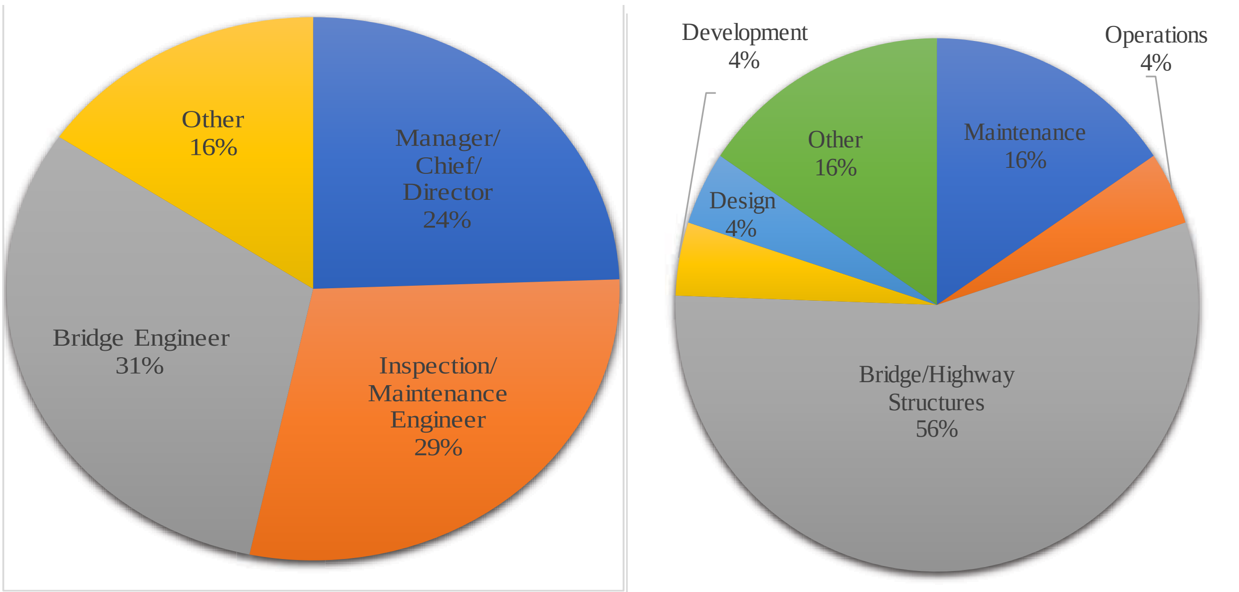


Figure B-2. Respondent Job Title (left) and Division (right). N=45 DOTs

B.2.2 Emergency Preparedness

This section of the questionnaire identified existing procedures and protocols each state currently implements. An understanding of the current methods is crucial to ensure that the developed guidelines are applicable to the concerns of these transportation agencies but also provide new information and bring in a fresh perspective to established routines.

First, respondents were asked if their transportation agency had any existing procedures related to planning, assessment, and/or rapid restoration of bridges in extreme events. Most DOTs (83%) had some form of planning procedures, and of these, several had documented procedures (14%). Many DOTs also had documentation for assessment (33%). However, more than 50 percent of respondents indicated their DOT has either no procedures or informal procedures with minimal documentation for planning and restoration. In addition, thirty-one percent indicated they had no formal or informal procedures with minimal documentation for emergency assessment. This indicates that agencies rely on an ad hoc approach to emergency event preparation, assessment, and rapid restoration (Figure B-3). If the agency indicated they had documented procedures, they were asked to send copy(ies) of these documents to the research team to incorporate into the Literature Review. Most documents submitted to the research team consisted of emergency response manuals, inspection guides, and state emergency plans.

Furthermore, the respondents were asked if their agency had a Plan of Action (POA) for scour critical structures. Most respondents (98%) indicated they did and were asked to provide copies or templates of example POAs to the research team (Table B-1). Most of the submitted POAs contained information such as bridge identification number, location, possible detour routes, scour threat level, and known scour-related issues. Some DOTs also mentioned they utilized scour monitoring programs such as BridgeWatch, a privately run software that helps identify and manage structures that are threatened by flooding or scour events.

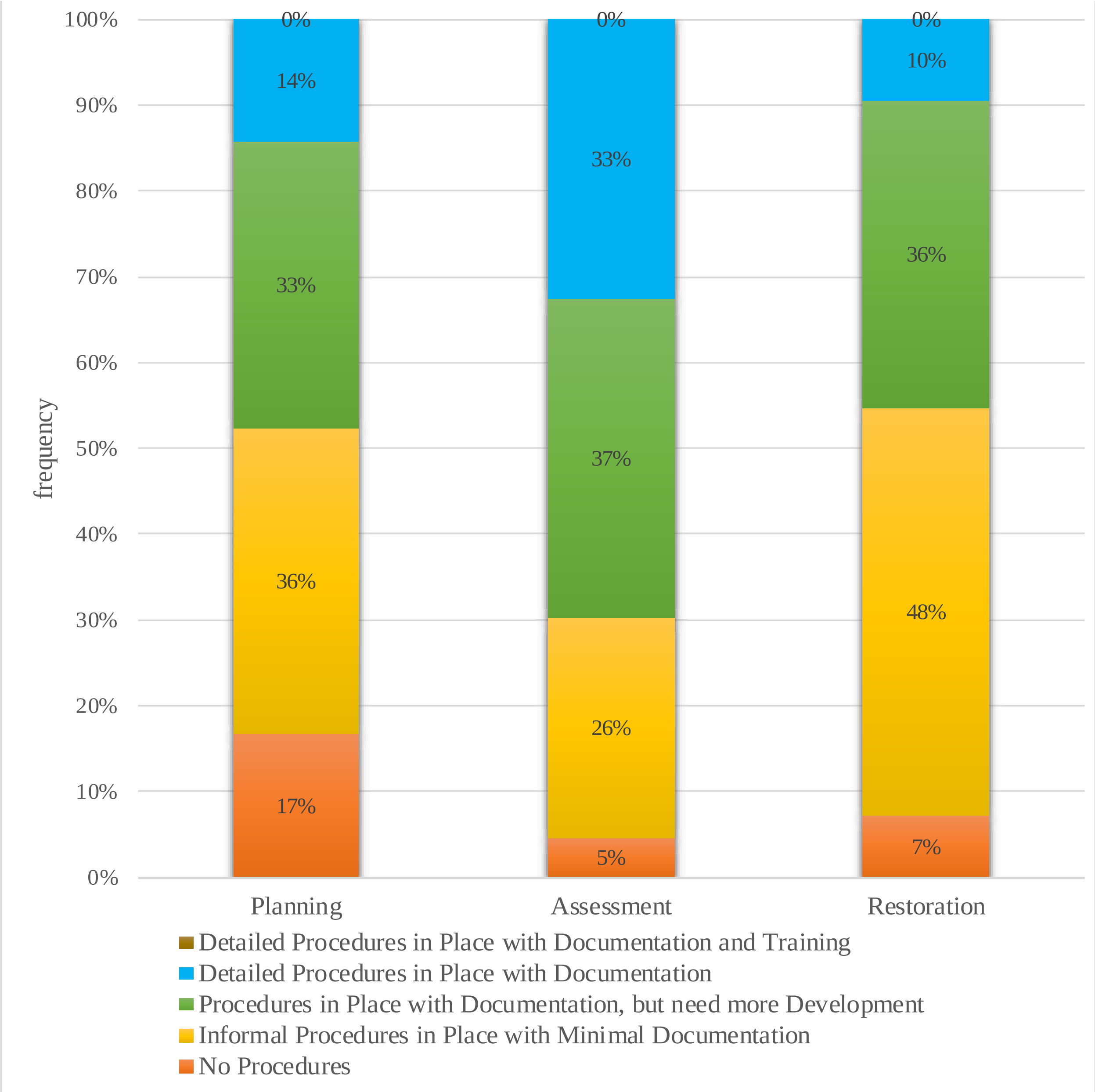


Figure B-3. Bar Chart on Current DOT Procedures for Emergency Event Procedures. N=43 DOTs.

Table B-1. Plan of Action for Scour for scour critical bridges and/or culverts. Current state. N=44 DOTs.

Response	Percentage
Yes	98%
No	2%
Not Sure	0%

Some DOTs indicated they have established training for emergency events as a form of emergency planning. Twenty-one percent of DOTs indicated they complete some form of annual training in preparation for extreme events, while thirty-seven percent said they had no require training (Figure B-4). For the DOTs that did indicate some level of training, most trained for extreme events such as flood (19), scour (17), and earthquake (13). Furthermore, out of the DOTs who indicated they trained for extreme events, most indicated they trained for multiple events (79%) (Figure B-5). It is important to note that not all extreme events listed are applicable to all DOTs. For example, threats of seismic events are significantly higher in westerns states like Alaska, Washington, Oregon, and California, whereas tropical storms like hurricanes are most common in the gulf regions of Louisiana, Texas, Alabama, Florida, and Georgia. However, the top two events (flood and scour) can occur in any region.

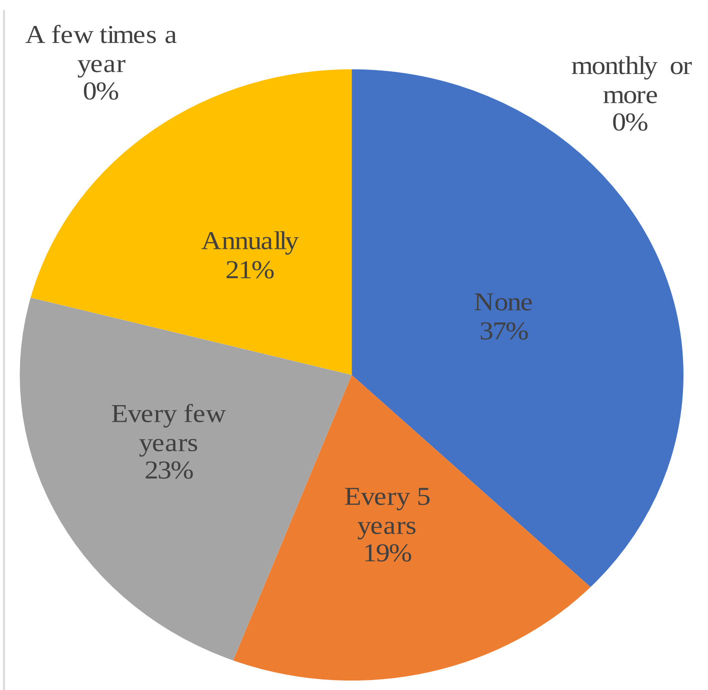


Figure B-4. Assessment Training Frequency for Emergency Events by State DOTs. N=43 DOTs.

B.2.3 Emergency Assessment

In this section of the questionnaire, respondents were asked about their procedures related to emergency assessment of structures during and after emergency events. These procedures include the technologies of other resources required to complete inspections and to make decisions regarding necessary repairs. When provided a list of common inspection technologies, respondents indicated they would most likely use unmanned aircraft systems (UAS) (67%), survey grade GPS/GNSS (57%), and smart devices without a specific app (53%). Technologies such as autonomous boats or underwater vessels (58%) and a smart devices with a specific app (48%) where unlikely to be used (Figure B-6). With the rise of popularity of mobile devices like tablets or cell phones in the field, the use of smart phones is not surprising. However, how these devices are used (photos, videos, notes) does vary, and the use of commercial apps does not appear to be significant at this time.

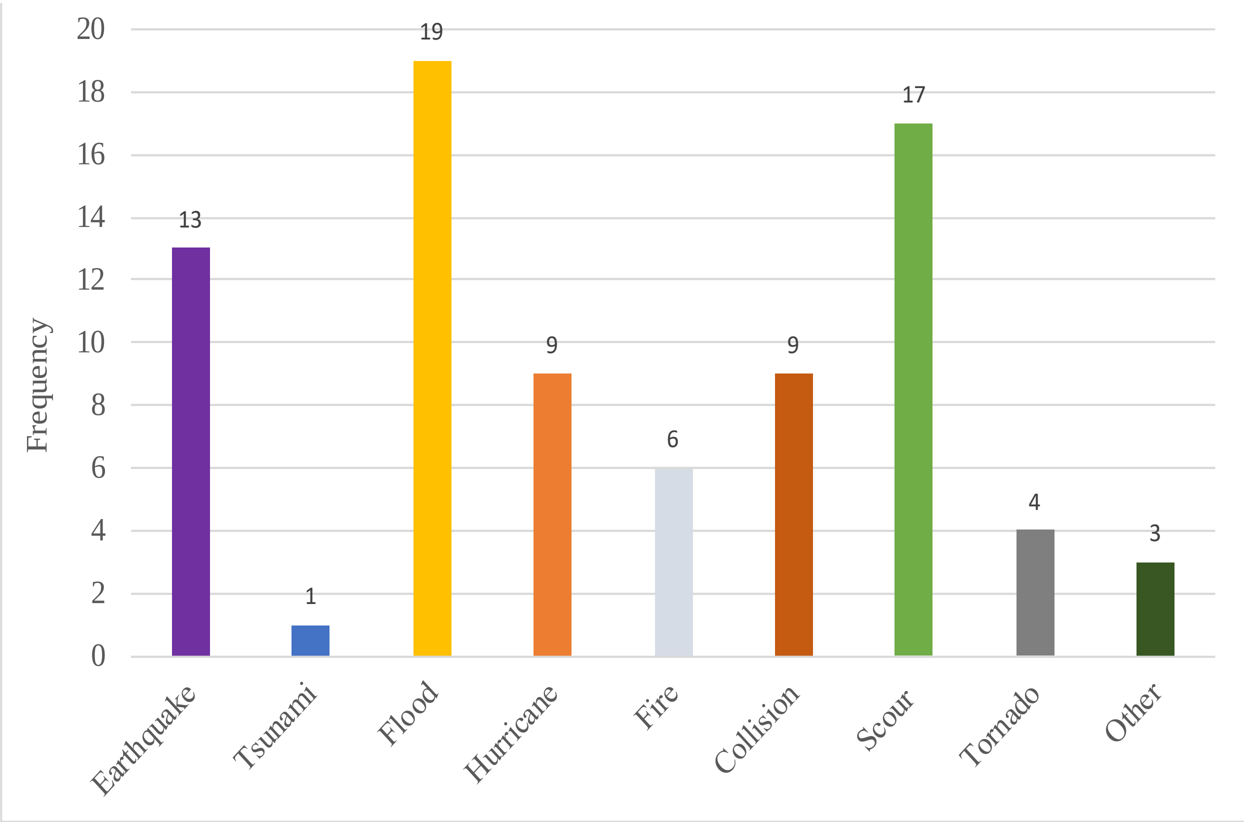


Figure B-5. Types of Emergency Events Trained for by State DOTs. N=28 DOTs.

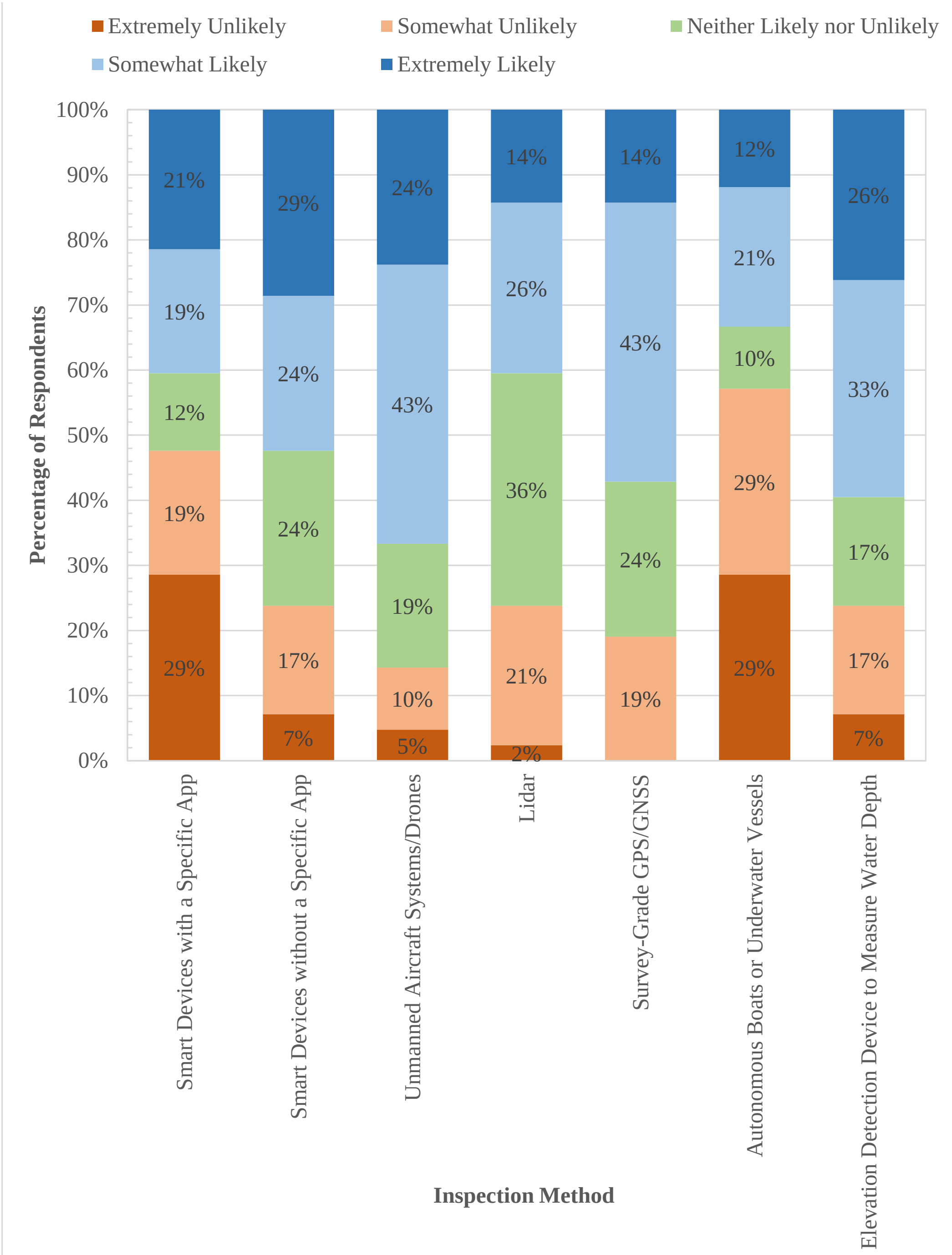


Figure B-6. Likelihood on Technologies Used for Emergency Inspections by State DOTs. N=42 DOTs.

For prioritizing structures, 50% of DOTs mentioned they use specific documents to help prioritize structures for inspection after emergency events (Table B-2). Many sent in examples of these documents. Depending on the type of emergency event, some prioritized structures based on distance from the storm path or seismic epicenter, while others looked at structure age and condition rating. Many DOTs have predetermined lifeline or supply routes. Structures along these roadways also received a higher priority, and others took functional class route into consideration. Furthermore, many DOTs mentioned their specific prioritization methods for scour critical structures. In these instances, the bridges are prioritized based on the POAs for each. Others relied on programs like BridgeWatch or weather forecasts to help predict which structures would be hit the worst. Using mapping software like ArcGIS helped identify structures in similar regions, or indicate already closed structures, which often have a higher priority.

Table B-2. State DOTs Documentation Availability for Ranking Structures Before/During/After Emergency Events. N=43 DOTs.

Response	Percentage
Yes	50%
No	43%
Not Sure	7%

To understand the challenges DOTs face during emergency assessments, respondents were asked to identify impediments they face. Of the provided list, prioritization (1^{st}), followed by contracting qualified contractors (2^{nd}) were ranked as the highest obstacles (Table B-3). In the "other" category, limited site access was also mentioned. This was in reference to instances where roads were impassable or other structures were too damaged to cross, restricting site access to the bridge in question.

Table B-3. Encountered Impediments to Bridge Inspections. N=36 DOTs.

Ranking	Response	Avg Ranking	Max	Min	Median	Standard Deviation
1	Prioritizing Structures to inspect	1.2	1	2	1	0.40
2	Contracting qualified contractors	5.0	1	9	5	2.41
3	Lack of technical expertise	5.1	1	9	6	2.77
3	Lack of in-house inspectors	5.1	3	9	5	2.39
3	Lack of guidelines	5.1	1	9	5	2.43
6	Lack of training	5.5	3	9	6	1.74
7	Other	5.9	1	9	6	2.09

Recently, *NCHRP Research Report 833* investigated the assessment, coding, and marking of structures in emergency situations, and is a foundation for this work. Respondents were asked if they were familiar with this report and if their DOT implemented any results that were developed. Respondents indicated that most have heard of the report (60%); however, only 14% have implemented some of the procedures at this time (Figure B-7). Some DOTs commented they follow similar established policies to *NCHRP Research Report 833*, but some of the terms and techniques may differ slightly. Other DOTs mentioned they use a comparable program, such as FEMA X or Mobile Solution for Assessment and Reporting (MSAR). The latter includes options for field data collection and provides access from any device. This program provides a collection of online forms, offline map viewing, and collaborative workflows aimed to help improve the efficiency of inspection teams and streamline the data collection progress.

B.2.4 Repairs

With rapid restoration, it is important to understand the current repair methods used by the DOTs. Respondents indicated that DOTs often use a similar procedures as routine repairs for a rapid restoration, as their work crews and contractors are most familiar with these methods (Table B-4 and Table B-5).

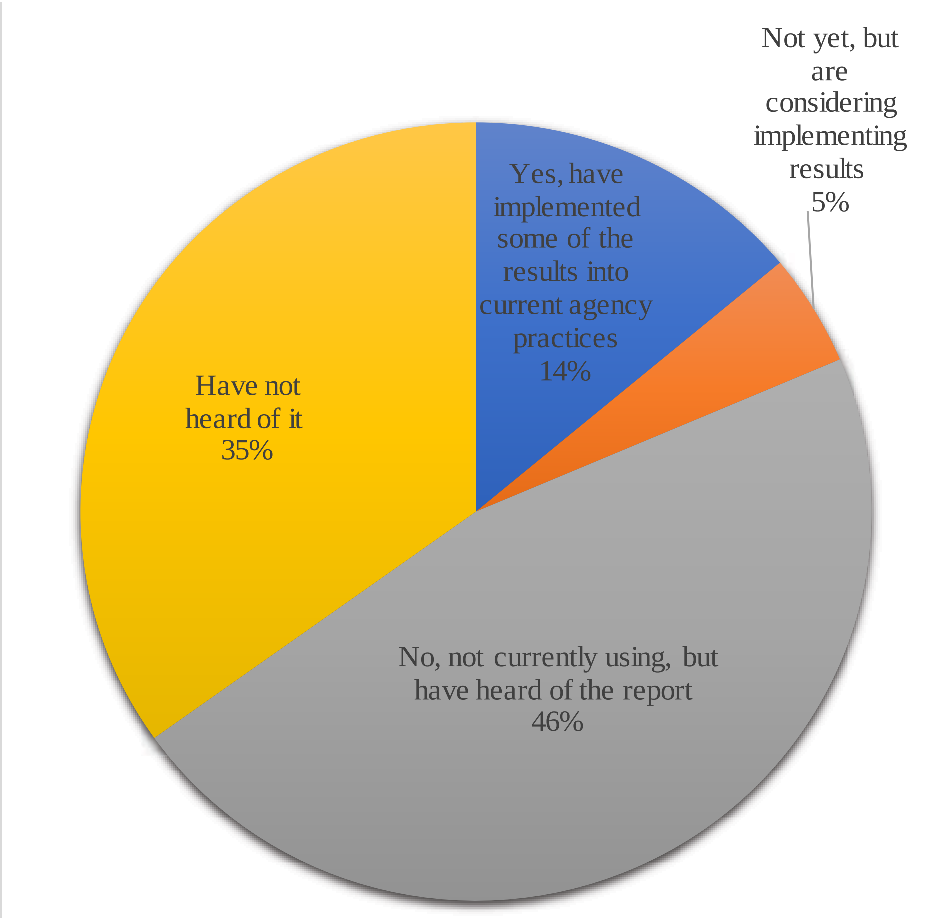


Figure B-7. Implementation of* NCHRP Research Report 833 *Procedures by State DOTs. N=43 DOTs.

Table B-4. External Work Completed on Behalf of States DOTs for Routine Repairs. N=44 DOTs.

Design & Engineering Documents		Performing Repairs or Construction Work	
Avg Percent	34%	Avg Percent	59%
Max	100%	Max	100%
Min	0%	Min	0%
Median	25%	Median	75%
Standard Deviation	29%	Standard Deviation	33%

Table B-5. External Work Completed on Behalf of State DOTs for Rapid Restoration. N=44 DOTs.

Design & Engineering Documents		Performing Repairs or Construction Work	
Avg Percent	37%	Avg Percent	65%
Max	100%	Max	100%
Min	5%	Min	5%
Median	30%	Median	75%
Standard Deviation	28%	Standard Deviation	31%

When making repairs, there are many factors that can be considered. Transportation agencies have a high consideration for limiting service interruption (84%), load capacity (55%), cost (48%), and time (48%) for routine repairs (Figure B-8). However, for rapid repairs, their concerns focus on time (90%) limiting service interruption (76%), and load capacity (57%) (Figure B-9).

Regarding types of restoration techniques, respondents indicated common construction practices (74%), accelerated bridge construction (ABC) (52%), emergency procurement procedures (45%), and accelerated versions of traditional design-bid-build (45%) are already implemented by many DOTs. Techniques such as delegation of authority (12%) were not as common (Figure B-10).

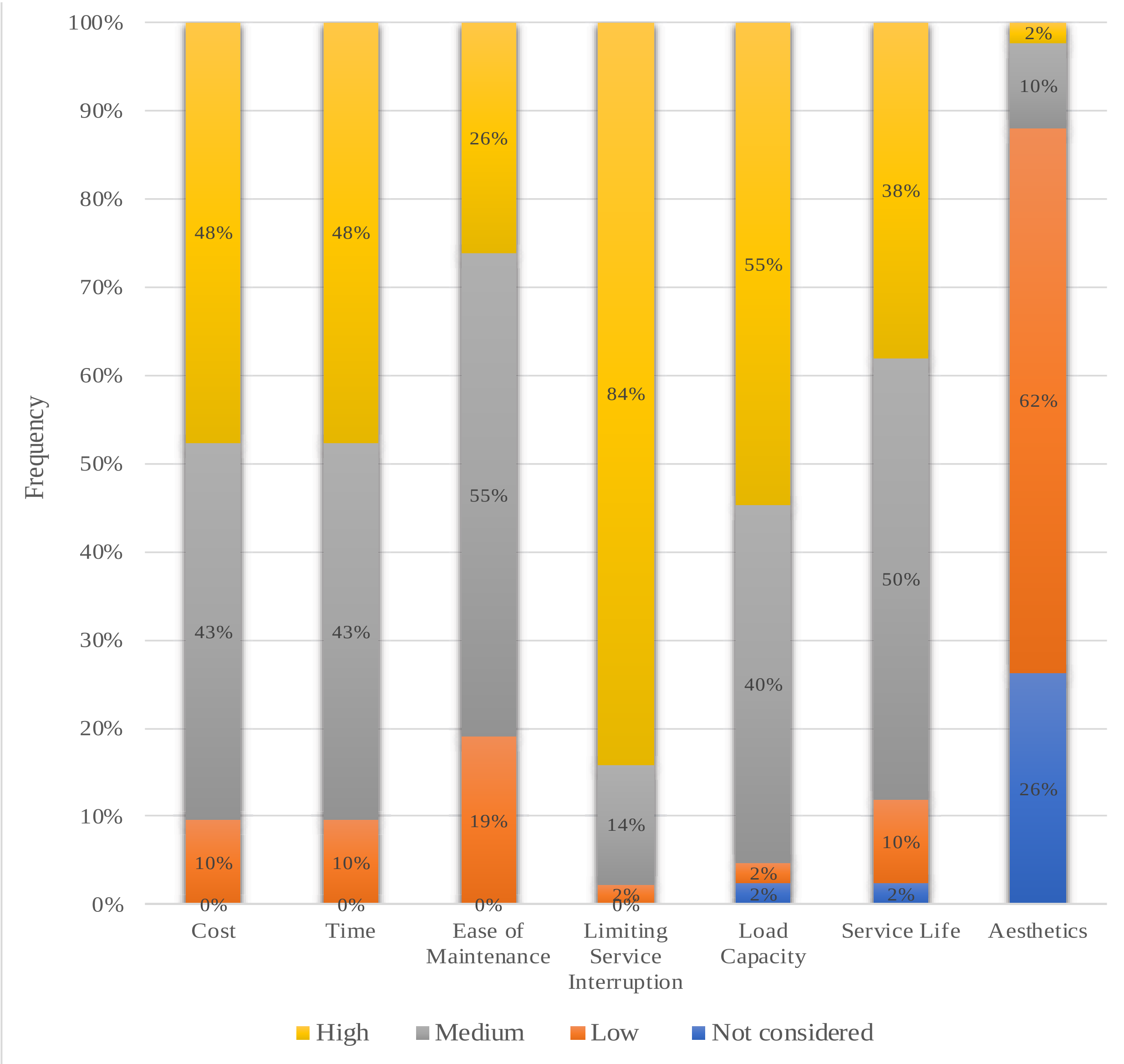


Figure B-8. Rating of Factors that Impact Routine Repair Methods. N=42 DOTs.

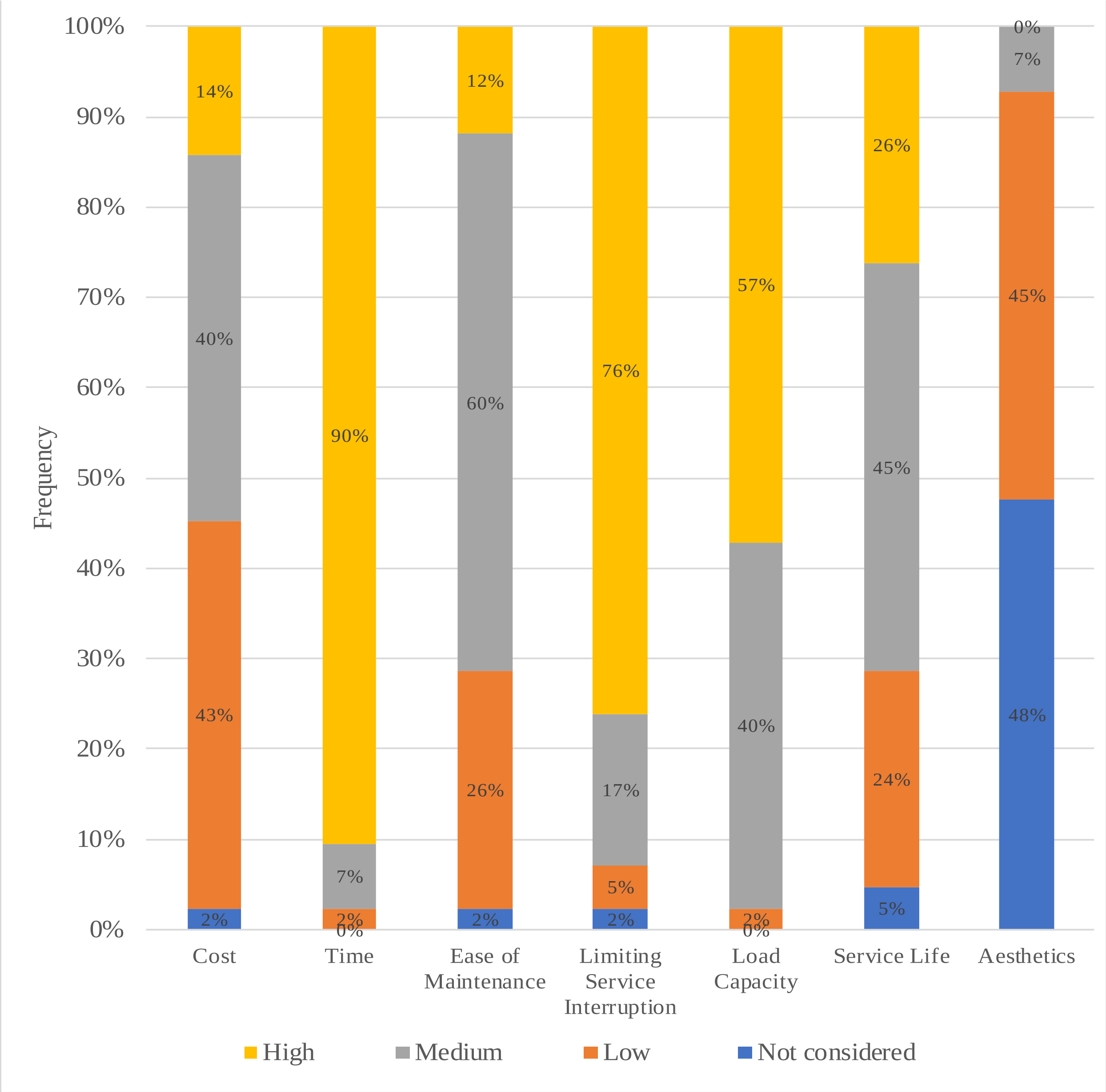


Figure B-9. Rating of Factors that Impact Rapid Restoration Methods. N=42 DOTs.

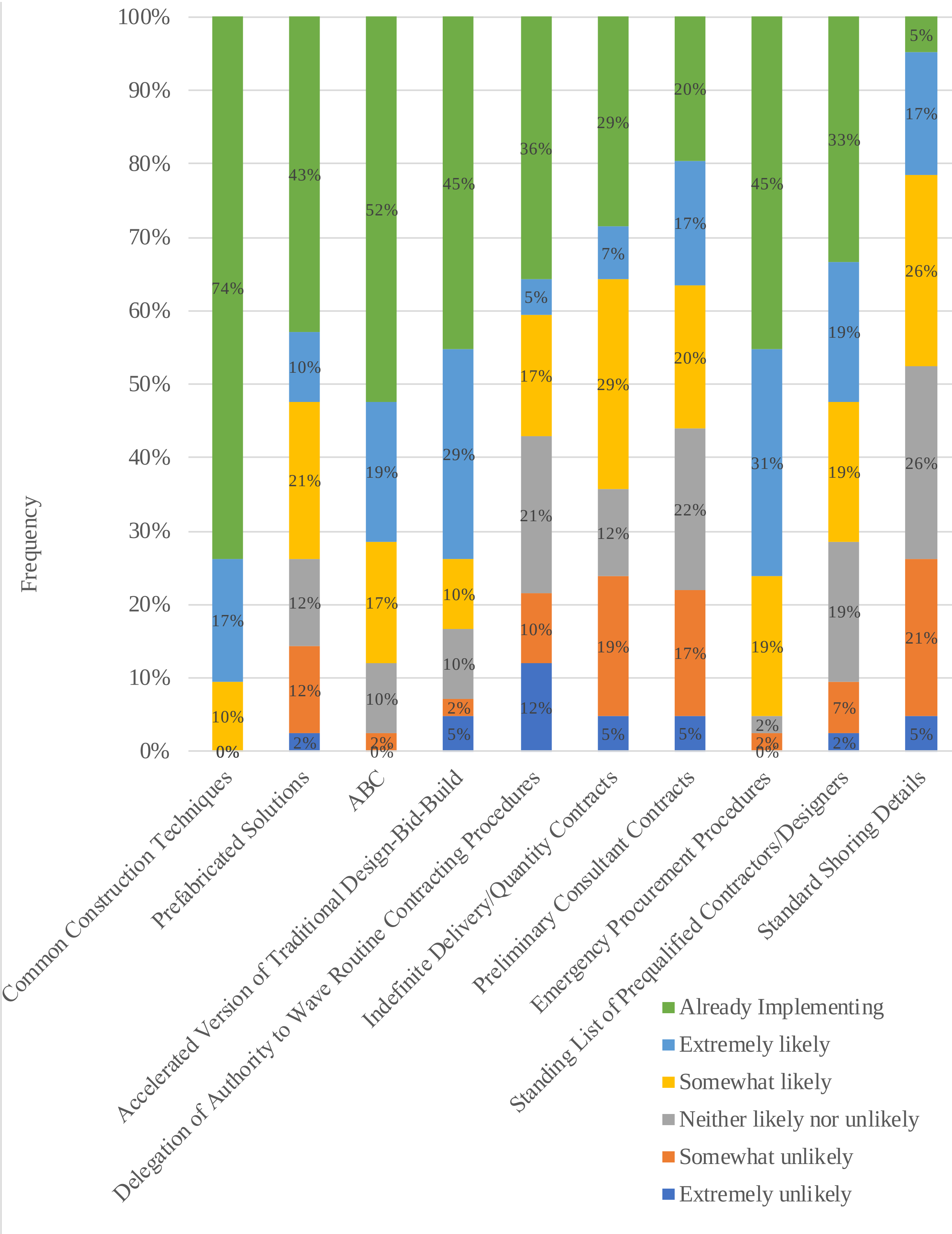


Figure B-10. Frequency of Likelihood of Using Listed Rapid Restoration Techniques/Procedures. N=25 DOTs.

There are a variety of impediments that can delay a rapid restoration project. Respondents indicated that procurement of materials (1st), contracting qualified contractors (2nd), and a lack of technical expertise (3rd) were the most substantial setbacks they encounter for rapid restoration projects (Table 2-11).

Table B-6. Encountered Impediments to Rapid Restoration. N=38 DOTs.

Ranking	Response	Avg Ranking	Max	Min	Median	Standard Deviation
1	Procurement of materials	1.9	1	7	1	1.32
2	Contracting qualified contractors	2.9	1	6	3	1.56
3	Lack of technical expertise	3.2	1	5	3	1.39
4	Lack of guidelines	3.8	2	5	4	0.93
5	Lack of training	3.9	1	6	4	1.47
6	Other	5.4	1	6	6	1.55

Other considerations, such as impeding factors that can delay the start of a project, also have an impact on rapid restoration projects. Respondents said that engineering review (1st), access to funding (2nd), and permitting (3rd) were the largest factors of the provided list (Table B-7).

Table B-7. Impending Factors for Rapid Restoration. N=39 DOTs.

Ranking	Response	Avg Ranking	Max	Min	Median	Standard Deviation
1	Engineering review or re-design	2.6	1	5	3	1.12
2	Access to funding	2.9	1	5	2	1.42
3	Permitting	2.9	1	6	3	1.57
4	Contractor mobilization	3.1	1	5	3	1.20
5	Inspection Progress	3.6	1	5	4	1.39

Some repairs require the use of long-lead items that must be ordered in advance, such as cast-in-place components. Different solutions are employed by DOTs to incorporate these items in their designs. Using temporary solutions (32%) and stockpiled materials (32%) were the most common methods identified (Figure B-11).

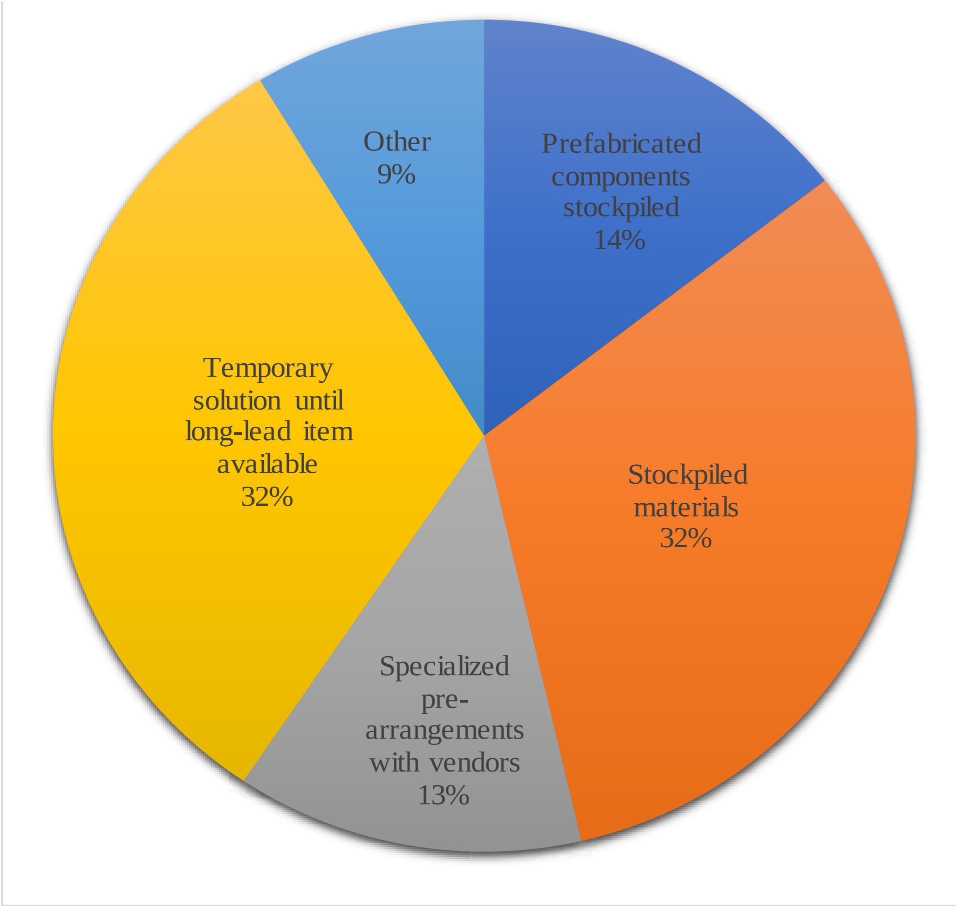


Figure B-11. Long-Lead Item Strategies. N=39 DOTs.

B.2.5 Case Studies

To better understand the current practices used by the transportation agencies, a series of questions were asked to identify potential case studies to be evaluated as part of Task 2. Most emergency events provided were from some form of structural collision, typically involving commercial vehicles (Figure B-13). The total duration for partial or complete restoration varied greatly among the case studies, ranging from days to years (Figure B-14). Visual inspections paired with cameras were commonly used to collect evidence (Figure B-12). However, there was not a strong link of assessment techniques, total duration of restoration, and type of emergency event, indicating many factors contribute to rapid restoration projects. This highlights how each specific instance has its own unique set of challenges.

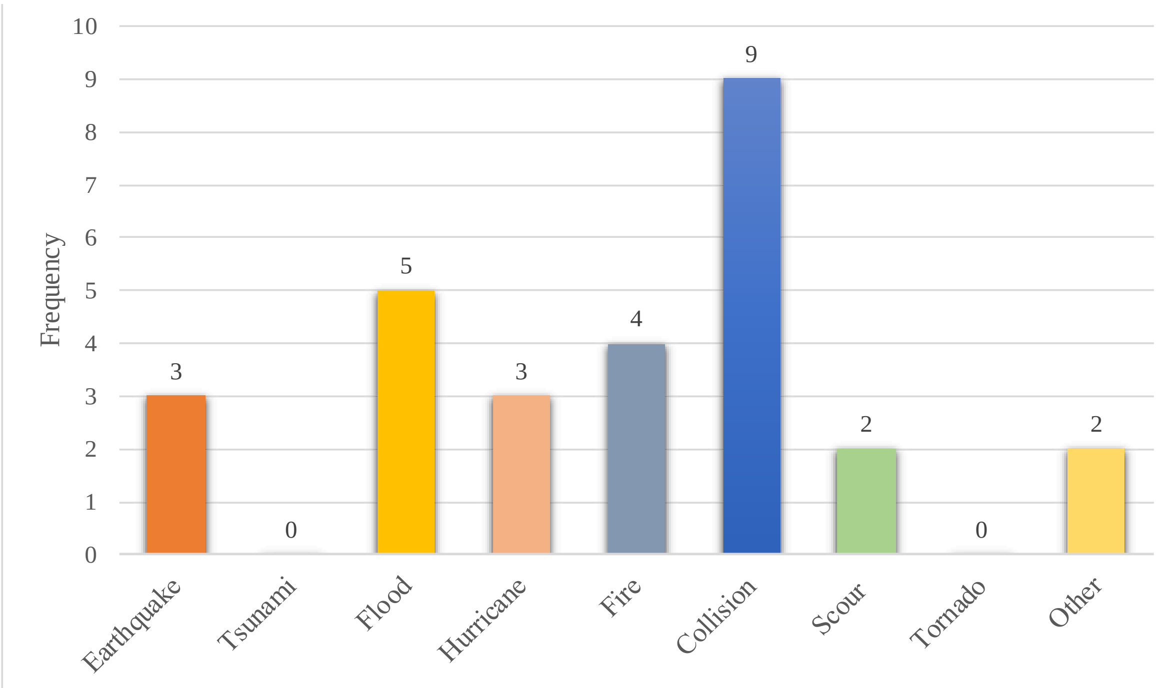


Figure B-13. Suggested Case Study of Emergency Event Type. N=28 DOTs.

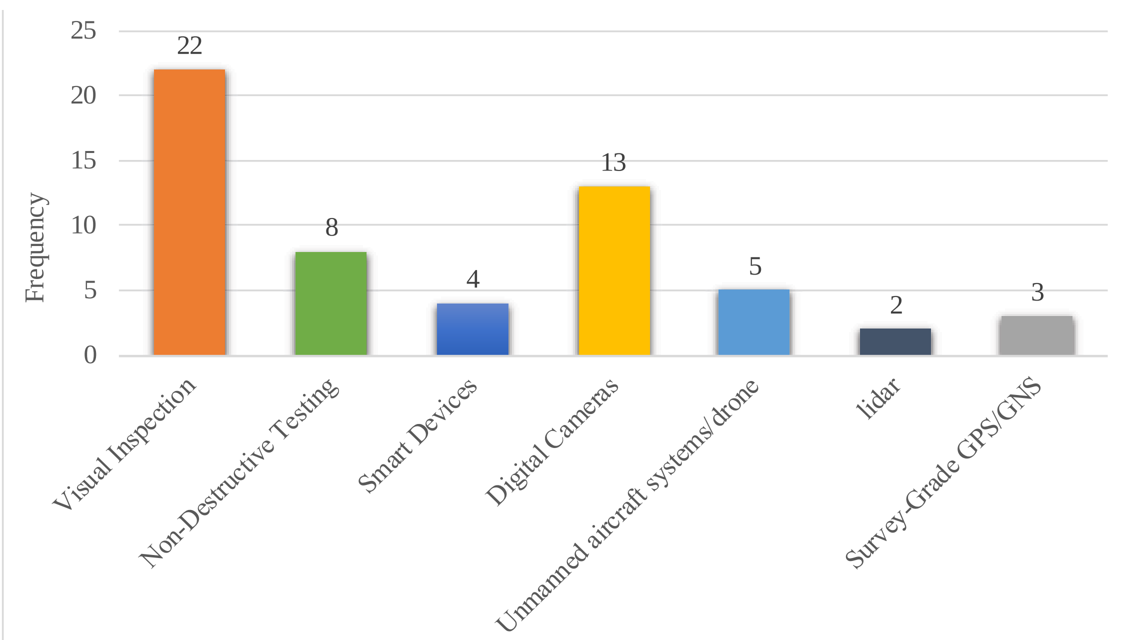


Figure B-12. Assessment Techniques Used in Selected Case Studies. N=22 DOTs.

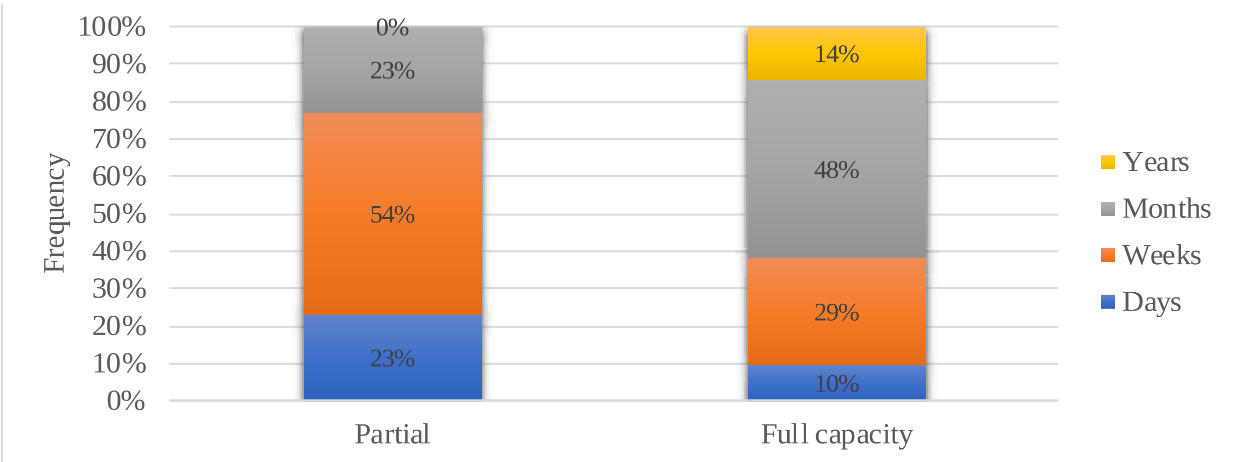


Figure B-14. Duration for Structure Restoration of Suggested Case Studies. N=13 DOTs for Partial and N=21 DOTs for Full Capacity.

B.2.6 Policy and Procurement

Acquiring required materials is a major component of a rapid restoration. Understanding each DOTs' current procurement processes can help identify the most popular choices, but also indicate the challenges often associated with these methods. Furthermore, there are a range of contracting types that can be implemented depending on the specific project. The most common types indicated by the questionnaire were traditional contracting methods (1st), maintenance crews (2nd), and ABC (3rd) for routine repair projects (Table B-8).However, for rapid restoration projects, design-build agreements (3rd) were added the most popular list, and maintenance crews dropped to 7th (Table B-9). These methods were also used in several of the case studies provided in question 16.

Table B-8. Ranking of Contracting Types and Methods for Routine Repairs. 1 = most likely. N=40 DOTs.

Ranking	Response	Avg Ranking	Max	Min	Median	Standard Deviation
1	Traditional Design/Bid/Let/Construction	2.3	1	5	2	1.11
2	Maintenance Crews	2.5	1	10	1	2.32
3	Accelerated Bridge Construction (ABC)	4.7	2	9	5	1.56
4	On-Call/Standby Contracts	4.6	1	8	4	2.35
5	Incentives or Disincentives	5.5	2	9	5	2.18
6	Design-Build Agreements	5.8	3	10	5	1.84
7	A+B Bidding (work + public impact costs)	6.4	1	9	7	2.07
8	Emergency Procurement Procedures	6.8	1	10	8	2.29
9	Indefinite Delivery/Indefinite Quantity Contracts	6.8	1	9	8	2.41
10	Other	9.6	1	10	10	1.50

Table B-9. Ranking of Contracting Types for Rapid Restoration. (1 = most likely. N=40 DOTs.

Ranking	Response	Avg Ranking	Max	Min	Median	Standard Deviation
1	Traditional Design/Bid/Let/Construction	2.8	1	8	2	2.49
2	Accelerated Bridge Construction (ABC)	3.3	1	9	2	2.3
3	Design-Build Agreements	4.1	1	9	4	1.84
4	A+B Bidding (work + public impact costs)	4.7	1	8	5	1.75
5	On-Call/Standby Contracts	4.9	1	9	5	2.55
6	Indefinite Delivery/Indefinite Quantity Contracts	5.7	2	9	6	2.30
7	Maintenance Crews	6.0	2	10	6	2.21
8	Incentives or Disincentives	6.1	3	9	7	2.17
9	Emergency Procurement Procedures	6.8	1	9	7	1.80
10	Other	9.9	6	10	10	0.17

B.2.7 Communications

During an emergency event, transportation agencies need effective communication procedures internally, with other agencies, with the public, and with first responders as part of disaster response, assessment, and restoration. Some of the most common communication methods for gathering information included crowdsourcing (96%) from a variety of sites such as social media (50%) and websites (21%) (Figure B-15A). Others used social media for sharing information to the public regarding closures and construction delays (48%), along with news broadcasting (23%) and websites (24%) (Figure B-15B). Other communication methods included in-person meetings, press releases, and department-specific liaisons to share information across multiple jurisdictions.

The use of tools can greatly improve the efficiency and effectiveness of response planning, assessment, and rapid restoration. Some DOTs indicated they did use a specialized tool such as an app, software, or flowchart, and others gave recommendations on what tool(s) they would find beneficial.

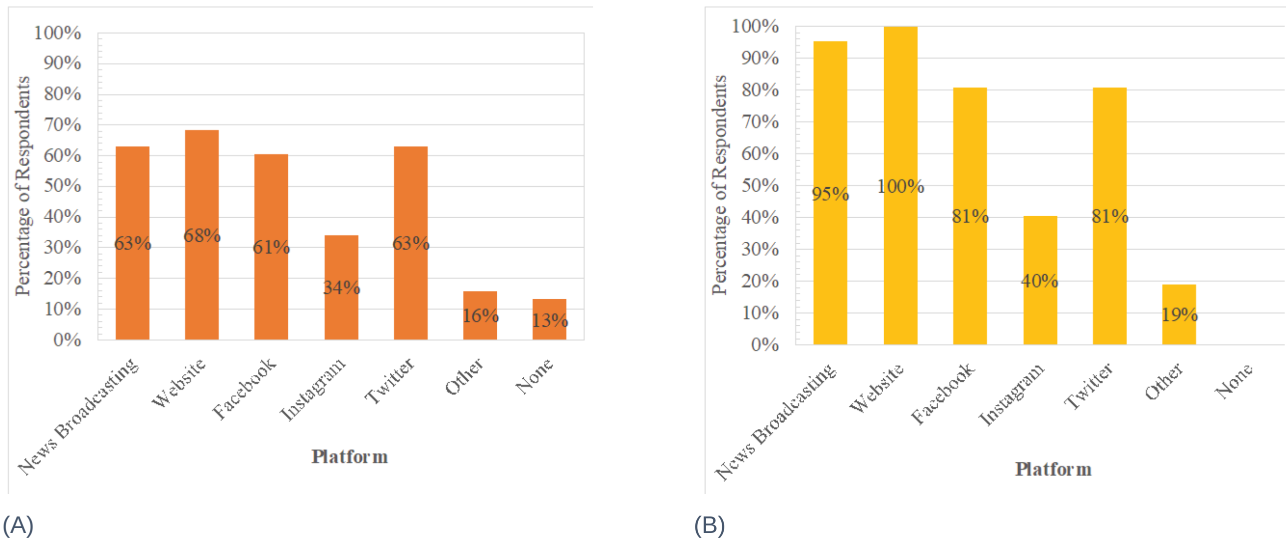


Figure B-15. Technology Used by State DOTs for (A) Crowdsourcing. N=38 DOTs and (B) Communicating Closures or Delays. N=42 DOTs.

Table B-10. Tools Currently Used or Desired in Extreme Events

Stage	Tools Used	Tools Desired
Planning	• BridgeWatch • Custom flowcharts • GIS mapping • Required equipment checklists • ShakeCast • Weather and traffic data reports	• Traffic impact tool that recommends personnel and equipment needed to inspect numerous structures
Assessment	• Bentley AssetWise • BridgeWatch • Custom flowcharts • GIS mapping • In-house data collection software • Mobile Solution for Assessment and Reporting (MSAR) • Overheight vehicle collision apps • RainShare • Remote control boats and underwater vessels • ShakeCast • Standard damage assessment forms and mobile device for electronic collection and reporting • Survey 123	• App that aligns with approach described in NCHRP Research Report 833 • Inspection app similar to InspectX
Rapid Restoration	• Custom flowcharts • Library of standards and design tools • Library of working drawings for beam impacts and other repairs • Survey 123	• Cost estimators • Database of shoring options • Prioritization methods

B.2.8 Overall Agency Self-Assessment

At the end, respondents completed a self-reflection on their ability to prepare, assess, and respond to emergency events. Most DOTs ranked their ability as fairly able and well-prepared, which indicates they feel that their agencies have made great strides to improve their overall resilience (Figure B-16).

DOTs were asked to provide suggestions for future training. Recommended formats included webinars and mock events. Content ideas included fund reimbursement procedures, improvements for communication protocols, event-specific disasters (especially those that are widespread and not as common), and general assessment guides. Additional suggestions included recommendations for DOT staff training frequency and implementation.

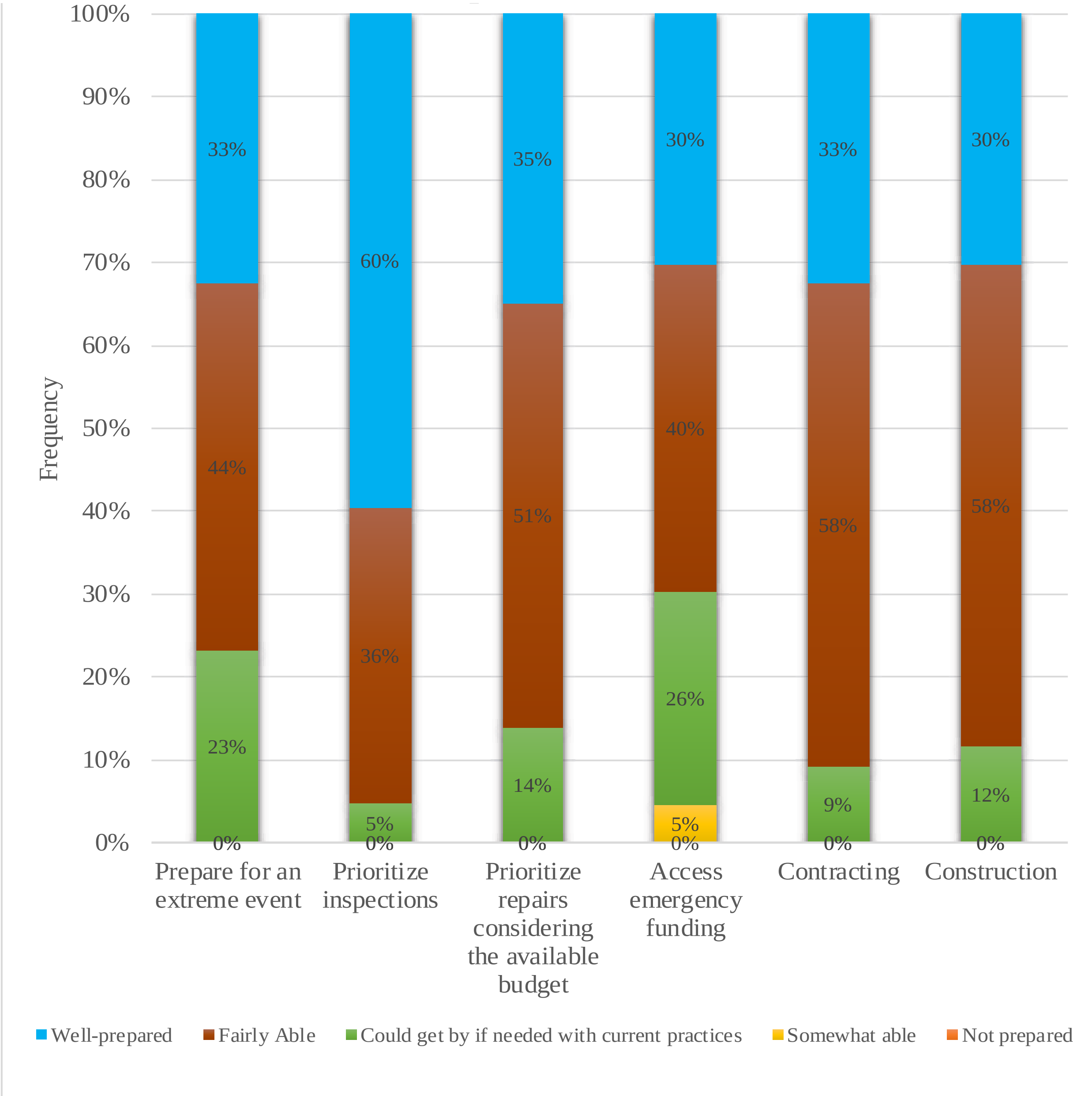


Figure B-16. State DOT Self-Assessment on Emergency Event Preparedness. N=43 DOTs

B.3. Conclusion

From the questionnaire, current practices and procedures were identified from the DOTs. These methods showcased which aspects the DOTs can invest their time, money, and resources in, but also which type of emergency events are most common in their respective regions. From this information, strengths and weaknesses can be evaluated as part of Task 2, which in turn will help lay the foundation for the Guidelines and corresponding tool developed for this project. The following observations can be generated from this questionnaire.

B.3.1 Emergency Preparedness

- Most DOTs do have documented procedures related to emergency planning, ranging from planning, assessment, and rapid restoration.
- Almost all DOTs have a Plan of Action (POA) for their scour critical infrastructure (98%).
- Most DOTs (37%) do not routinely train for emergency events, and the ones who do, complete training on an annual basis. Events that are commonly trained for are earthquakes, floods, and scour-related incidents.

B.3.2 Emergency Assessment

- To prioritize structures, half of the DOTs have some form of documentation (50%) to aid in prioritization of structural inspections. These methods range by distance from emergency event to bridge age and condition assessment.
- For conducting emergency inspections, the most common inspection technologies were unmanned aircraft systems (67%) and autonomous boats (57%).
- Impediments most common during inspections were prioritization (1^{st}), contracting qualified contractors (2^{nd}), and lack of technical expertise (3^{rd})
- Most DOTs have not yet implemented procedures based on *NCHRP Research Report 833* (81%).

B.3.3 Repairs

- Repair methods involving external work (by consultants, etc.) showed little to no change in the breakdown between routine repairs and rapid restoration methods.
- The factors most important for routine repairs were limiting service interruptions (84%), load capacity (55%), cost (48%), and time (48%), but for rapid repairs were time (90%), limiting service interruptions (76%), and load capacity (57%).
- Common rapid restoration techniques that DOTs already implement include common construction techniques (74%) and ABC (52%).
- The largest impediments associated with rapid restoration include material procurement (1^{st}), contracting qualified contractors (2^{nd}), and lack of technical expertise (3^{rd}).
- Impending factors associated with rapid restoration included engineering review (1^{st}), funding (2^{nd}), and permitting (3^{rd}).
- To prevent delays for long-lead items, DOTs use stockpiled materials (32%) and temporary solutions (32%).

B.3.4 Case Studies

- The suggested case studies provided were predominately commercial vehicle collisions that greatly varied in full restoration duration, from days to years due to unique factors with each incident. Case studies are included in the *Bridge Assessment and Rapid Restoration Tool* (BARRT).

B.3.5 Policy and Procurement

- The most common types of contracting methods for rapid restoration includes traditional design/bid/let/construction (1^{st}), ABC (2^{nd}), and design-build agreements (3^{rd}).

B.3.6 Communications

- Most (96%) of DOTs use some form of crowdsourcing methods as a means of gathering information
  - Of those, social media (50%) and websites (21%) were the most popular platforms

- To communicate delays and closures to the public, most DOTs use news broadcasting (23%), social media (48%), and websites (24%)
- Most DOTs do not use some form of a tool (flowchart, apps, software) to aid in either response planning, assessment, or rapid restoration.
  - If a tool were to be developed, the most popular suggestions include connections to commercial software, such as Bentley AssetWise, Survey 123, and BridgeWatch

B.3.7 General Conclusions

- Most DOTs rank themselves as fairy able to well-prepared to handle an extreme event. The area of lowest ranking was access to funding (5% somewhat able)

Overall, the questionnaire identified some gaps in planning for emergency events such as training, applying new and emerging technologies to emergency assessment and rapid restoration, harnessing the power of social media and other platforms to gather and share information, and using some form of a tool to aid in overall emergency preparedness. Another interesting finding was the stark contrast of limited documents for structure prioritization as compared to the highly rated self-reflection of the DOTs' ability to handle the task. This may indicate that many DOTs may not have documented procedures, but act more on an ad hoc basis, and operate from experience or memory rather than recorded policies. This works well with experienced personnel, but with newer employees or less frequent events, this may leave a gap in response and restoration capabilities. Developing guidelines can help shed some light in these areas, helping to bring DOTs across the county to improved levels of resilience.

Appendix C: Case Studies

C.1 Denali 2002 [Earthquake]

Table C-1. Denali Earthquake.

Case Study Name/Date	Denali Earthquake (2002)
Location	Alaska, USA
Event Type	Earthquake
Bridge Name	Tok Cutoff Bridge & Tanana River Bridge
Scope/Costs	Six bridges damaged, two discussed in this report
Planning Techniques/Tools	Incident Command System (ICS) training for some officials
Event Response	Use of ICS with inspection stations to deploy inspectors across the state rapidly
Assessment Techniques/Tools	Visual Inspections
Rapid Restoration Type	Immediate temporary repairs followed by permanent repairs
Innovations	• Using the ICS to set up inspectors across the state to be able to access the damage quicker • Multijurisdictional inspections to sped up assessment process

C.1.1 Introduction

On November 3rd, 2002, a 7.9 magnitude earthquake occurred on the Denali Fault in Alaska. This very large seismic event was felt as far as Pennsylvania and Louisiana and provided the Alaska Department of Transportation and Public Facilities (ADOT&PF) officials with the opportunity to test their Incident Command System (ICS) procedures and identify areas that could be improved. Not all responders received formal ICS training before the earthquake, so many were learning on the fly. Crews adapted quickly, and all 200 damaged bridges received Level II inspections to confirm initial damages reported within 48 hours of the earthquake. (McCarthy 2003).

C.1.1.1 Event Response

About an hour after the earthquake, Alaska DOT&PF formed an Emergency Operations Center (EOC) in conjunction with the Alaskan State Troopers, the media, and the public, to keep everyone informed as changes arose (McCarthy 2003).

After the EOC was established, the Alaska DOT&PF maintenance crews followed the ICS model to establish stations across the state as bases for inspections. Officials also adhered to the Alaska Emergency Operations Plan to guide state and local authorities on how to respond to a major earthquake and used the State's Emergency Highway Traffic Regulation, which provided guidance on deploying the military to help manage traffic in such situations (McCarthy 2003).

C.1.2 Emergency Planning

To prepare for a seismic event, Alaska DOT&PF had established the Emergency Operations Plan and an Emergency Highway Traffic Regulation Manual to guide officials during the event. These procedures and documents followed the nationally recognized ICS approach to emergency response and were utilized in the response.

C.1.3 Assessment

Level I inspections of bridges in the area were conducted by Alaska DOT&PF maintenance foremen. Level I inspections consisted of visual inspections looking for cracks, settlement, and embankment slides. Any major damages were quickly reported, and maintenance crews fixed temporary repairs on the spot in many cases. All temporary repairs and Level I inspections were completed within 24 hours. This efficiency was made possible by the establishment of inspection stations (McCarthy 2003).

After the Level I inspections were completed, Level II inspections were conducted on structures with higher levels of damage by members of the Bridge Design Section of the Alaska DOT&PF. These crews flew up from Juneau and completed all Level II inspections within 48 hours (McCarthy 2003), which included assessments of over 200 bridges (Alipour 2016). Because the main priority was to reopen transportation routes in Alaska, jurisdictional barriers were set aside such that inspections were not limited to state-owned bridges but also included several city and county structures. Footprints left in the snow confirmed which bridges had already undergone a Level I inspection before Bridge Engineers had arrived to complete Level II inspections (McCarthy 2003).

C.1.4 Rapid Restoration

C.1.4.2 Permanent Structure

During inspections, two bridges were identified as needing replacements. These structures failed due to their sheet pile wall abutment design, which suffered severe lateral displacement due to liquefaction. Even though they were deemed safe enough to carry traffic loads, the Alaska DOT&PF decided to replace the structures, as officials were skeptical if the bridges could withstand another earthquake. Several other bridges suffered minor to moderate damage, including the Tok Cutoff Bridge, whose abutment moved ten inches from its original position (Figure C-1). This displacement caused an increase in stresses on the superstructure, requiring crews to replace two spans of the bridge (Alipour 2016).

Figure C-1. Shifting of the Tok Cutoff Bridge (McCarthy 2003)

One truss bridge experienced a shifted rocker bearing. Luckily, the shifted pin and bearing did not separate, so maintenance crews were able to jack the bridge up and push the pins back into their original slots. Old railroad rails were welded together and used as piles in the original construction. However, these failed a few years later due to the brittle material and had to be replaced during the repair.

The steel supports of a span of the Tanana River Bridge, built in 1943, shifted four inches. For the repair, the span (weighing 1.1. million pounds) was lifted back into its original place followed by installation of lateral restraints and repair of expansion joints (McCarthy 2003).

C.1.5 Challenges

The most challenging aspect of coordinating the response of the Denali Earthquake was the transition between the response and recovery phases. With many moving pieces, it was difficult to manage multiple jurisdictions and to communicate clearly to ensure everyone was on the same page. Furthermore, only those officials in the northern part of the state had any formal ICS training; many were learning on the job. Despite this lack of experience, crews adapted quickly and were able to provide a controlled and efficient response (McCarthy 2003).

Another challenge was the weather conditions. Luckily, crews did not have to fight a snowstorm, but the unknown weather forecast forced a rapid repair process. Furthermore, most Alaskan maintenance does not take place during the winter. Crews had to learn not only how to make these mid-season fixes, but also how to repair them again in the spring and summer, as many were meant to be temporary or did not survive the harsh winter (McCarthy 2003).

C.1.6 Innovations and Lessons Learned

C.1.6.3 Emergency Response and Management

Most of the lessons learned from the Denali Earthquake were related to emergency response and management. Improved record keeping of damages for cost-estimates and coordination with inspectors and recorders was needed, as in many instances, repairs were already completed by maintenance crews before photos could be taken of the damage. Additional training for all officials and mandatory ICS training were later required for crews after the earthquake to improve the preparations for the next event (McCarthy 2003).

C.2 Japan 2011 [Earthquake and Tsunami]

Table C-2. Japan Earthquake and Tsunmai

Case Study Name/Date	Japan Earthquake and Tsunami (2011)
Location	Japan
Event Type	Earthquake/Tsunami
Bridge Name	Several
Scope/Costs	About 200 bridges total damage
Planning Techniques/Tools	N/A
Event Response	Multiple global and local research teams to analyze and assess the damage
Assessment Techniques/Tools	Visual inspection, photographs, and videos
Rapid Restoration Type	Temporary structures, FRP repairs
Innovations	• Mass deployment of temporary structures • Importance of retrofits to reduce likelihood and extent of damage

C.2.1 Introduction

On March 11, 2011, the 9.0 magnitude Great East Japan Earthquake struck much of the nation. The earthquake subsequently caused a tsunami, destroying entire communities, as shown in Figure C-2. Imposing enormous damage and causalities, the earthquake and tsunami left with an opportunity for researchers and practitioners to verify the resilience of structures and infrastructure. Amid many other factors, researchers were able to investigate the effectiveness of the seismic design features added to many structures after the 1978 Miyagi-ken-oki and 1995 Kobe earthquakes and how to implement tsunami-resilient structures in the future. One piece of evidence for ‘good practice’ is that many of the bridges that did not sustain severe damage in the 2011 earthquake had been repaired or retrofitted after the 1978 and 1995 earthquakes, showing the benefits of lifecycle intervention measures (Kawashima & Matsuzaki 2012).

Figure C-2. Utatsu Bridge Flooded (Kawashima & Matsuzaki, 2012)

C.2.1.1 Event Response

Many disaster reconnaissance teams consisting of researchers and professionals were quickly deployed after the earthquake and tsunami to assess and analyze the damage. Teams were made up of domestic and global members from different professions of Civil Engineering. Most teams were ground-based, and major reconnaissance techniques included the use of digital photos/videos at the ground level. Many first responders were assisted by the geospatial tools and remote sensing products. Some performed numerical analyzes to better understand what occurred.

C.2.2 Emergency Planning

C.2.2.2 Crowdsourcing and Information Gathering

During the earthquake and tsunami, witnesses captured photos and videos of the damage. Many local citizens posted striking images and videos on social media including Twitter, Facebook, and YouTube, which broadcasted to the international community timely and vividly about the severity of the disastrous forces, from the seismic shaking to the tsunami waves. Security cameras were another source for collecting real-time evidence. This imagery data was then analyzed to better understand what caused some structures to fail (or in some cases not), and to see where future designs could be improved for building or retrofitting more resilient earthquake and tsunami structures.

C.2.3 Assessment

Most of the damage assessment was based on visual inspection in the field, photographs, and videos. In some cases, buoyancy calculations were conducted to verify the cause of uplifting of spans from the tsunami. Seismic loads were also calculated, and these considered the dead weight of the structure, the elastic seismic coefficient, and an overstrength factor (Kawashima and Matsuzaki 2012).

Japan breaks down its bridge damage levels by the damage states of A, B, C and D. Each damage state has a corresponding description for either concrete piers or concrete girders describing what damage would occur with that damage state. For flexural and shear failures, damage degrees were assigned based on visual observations (Saini and Saiidi 2013).

C.2.3.3 Earthquake Damage

C.2.3.3.1 Yuriage Bridge

At the Yuriage Bridge, tsunami waves passed under the structure, but were not intense enough to generate any significant damage, and the observed damage was attributed to seismic motions (EERI 2011). This damage was concentrated at the steel roller bearings. Seismic motions built up stresses at the bearings, where failure was observed. The bridge also experienced damage at the ends of its prestressed girders, which was attributed to radial stresses originating at the bearing (Kawashima 2012). The bearing damage was also thought to be caused by pier movement, which was caused partially by liquefaction. This caused a vertical shift on the deck of 6 cm, and a horizontal shift of 5cm. These measurements were performed during field visits as shown in Figure C-3A (Japan Bridge Engineering Center 2011).

C.2.3.3.2 Tennoh Bridge

This steel bridge suffered rupture and local buckling to its braces. One of the gusset plates also disconnected due to corrosion and torsion, as shown in Figure C-3B (Kawashima 2012). Bearing bolts also fractured, and their chunks were laying near the connections. The expansion joint protector was dislodged due to these fractured bolts. On the bridge deck, the teeth-like expansion joint suffered extreme separation from longitudinal motion (Japan Bridge Engineering Center 2011).

Figure C-3. Earthquake Damage Observed Yuriage Bridge Damage (Japan Bridge Engineering Center 2011)

C.2.3.3.3 Sendai-Tobu Viaduct

The viaduct was under construction during the earthquake. It was being widened, and the crews were in the process of connecting the on and off ramps before the disaster (Kawashima 2011). The set-up of construction scaffolding did make it easier to access the bridge for inspection (Kuwabara and Yen n.d.).

The elastomeric bearings ruptured and detached from their steel plates. This was attributed to extreme relative displacements between the deck joints in the transverse direction, which led to great shear forces (Kawashima 2012). Additionally, extreme tension forces were also found to play a role in the failure. In total, 18 elastomeric bearings and 40 of the steel stoppers failed. Furthermore, the spans with two different types of bents (in this case hammer head vs. pier) behaved differently, creating torsion demands in the superstructure which added stress to the bearings (EERI 2011).

C.2.3.3.4 Shida Bridge and Levee

Visual inspections found that one of the fixed bearings dropped off their seats, and another suffered sheared anchor-bolts. Also, one of the abutments settled, which was caused by reduced soil capacity. These factors led to a highly visual drop in the road deck at pier 3. At other pier locations, there was some severe cracking and yielding (EERI 2011).

C.2.3.3.5 Ezaki Ohashi Bridge

This 9-span continuous bridge suffered shear cracks, concrete spalling, and buckled longitudinal bars at the piers. To repair the columns, confining Fiber-reinforced polymer (FRP) was used to increase their axial capacity, creating a smooth finish (Kuwabara & Yen n.d.).

1.1.1. Tsunami Damage

C.2.3.3.6 Utatsu Bridge

The Utatsu Bridge suffered a flexural failure at one of the columns as shown in Figure C-4, even though it was seismically retrofitted prior to the tsunami and earthquake. This failure was assumed to be caused by the seismic motions, which weakened the structure. The following tsunami then damaged the adjacent span 3 and washed away 8 spans in total (Japan Bridge Engineering Center 2011). Most of the span damage and uplift was caused by the deformation of lateral seismic restraints which freed up the spans to be pushed off their bearing. This unseating was caused by either the tsunami lateral forces or just buoyant forces (Kawashima 2012 and Japan Bridge Engineering Center 2011). The bridge was retrofitted a few years before the tsunami, and cable restraints were added between the spans that eventually washed away. Some of the restrainers ruptured, but others stayed intact, and the washed away spans were found still connected downstream of the flow (Kawashima and Matsuzaki 2012).

Figure C-4. Fuji Bridge Damage (Kawashima & Matsuzaki, 2012)

A video captured the Utatsu bridge being inundated by the tsunami. Eventually, the entire bridge was engulfed in the waves (Figure C-2). From the video, the flow velocity was calculated to be about 6m/s (Kawashima and Matsuzaki 2012).

C.2.3.3.7 Koizumi Bridge

The Koizumi Bridge had been seismically retrofitted with hydraulic dampers at the abutments before the event. However, these enhancements could not withstand the inundation by the tsunami, which washed away all six spans of the bridge. A site investigation conducted revealed that most of the spans were lifted off their piers from the upward forces produced by the tsunami. The lateral restrainers from shear keys and dampers could not compete with the lateral tsunami forces; once freed from lateral restraint, the spans were floated away from the vertical forces (EERI 2011). One of the main channel piers was washed away after deep scour was formed (Japan Bridge Engineering Center 2011).

Figure C-5. Koizumi Bridge Damage (Istrati et al. 2017, photo by E.V. Monzon)

To restore traffic and post-disaster recovery, a temporary structure was built to move people and goods after the tsunami (Figure C-5) (EERI 2011).

C.2.3.3.8 Nijyu-ichihama Bridge

The tsunami washed out the backfill behind both abutments, causing the single span bridge to look like it had three spans (EERI 2011). Extreme scouring occurred at the piers as well, and these were later repaired by pouring new concrete around the damaged and exposed footings (Japan Bridge Engineering Center 2011). To restore traffic, temporary steel I girder approach spans were set in place, and temporary steel towers were also erected for additional support (EERI 2011).

C.2.3.3.9 Kawahara River Bridge

This bridge was struck by a floating two-story building, but surprisingly only suffered minor damage from this impact. Most of the damage was caused by the dramatic erosion of the embankment fill. A temporary bridge was installed adjacent to the structure (Kawashima 2011).

C.2.4 Rapid Restoration

C.2.4.1 Temporary Structure

As documented above, temporary bridges were deployed in several cases to aid in relief (the Koizumi, Nijyu-ichihama, and Kawahara bridges). Permanent repairs or replacements were implemented later.

C.2.4.2 Permanent Structure

Repair efforts were generally very quick across the nation. By March 24th, about 94% of repairs had been made for slight to moderate damage; restoration measures for extreme damages were completed by March 30th (Kazama and Noda 2012).

Japan does have a guide for repairing reinforced concrete piers based on the damage states (D) and damage degree assigned during the inspection period. A simple chart is used to determine the best recommended restoration procedure, which ranges from reinforced concrete jacketing, resin injection, and FRP (Saini and Saiidi 2013).

C.2.5 Challenges

Initially, the destruction from the combined earthquake and tsunami events was so widespread. Therefore, it was difficult to determine where to start disaster relief efforts. Furthermore, some structures required an in-depth analysis to determine if the damage was caused by the earthquake or tsunami. This is important to understand the robustness of these structures, and to learn if previous retrofits (if applicable) did show improvements to design and reduced the level of damage.

C.2.6 Innovations and Lessons Learned

C.2.6.3 Elastomeric Bearings

Bridges that used elastomeric bearings were found to be less likely to suffer earthquake motion damage, as shown in Figure C-6. Bridges that included dampers or other seismic force reducing devices also tended to perform better (Kawashima 2012). The use of elastomeric bearings was implemented extensively after the 1995 Kobe earthquake, as they also tended to perform better in that earthquake (Kawashima 2011).

Figure C-6. Elastomeric Bridge No Damage (Kawashima & Matsuzaki 2012)

C.2.6.4 Scour and Buoyancy Damage Mitigation

Structures that were taller than the tsunami waves and short in length outperformed their counterparts with opposite dimensions. Most of the damage caused by the tsunami waves was extreme erosion of embankments due to lack of scour protection (rip rap, etc.). Common scour countermeasures would help mitigate some of the effects of erosion. To prevent buoyant forces from causing the unseating of bridge girders, vertical restrainers are recommended for future bridge designs (Kawashima 2012). However, for some of the older bridges, the substructures may need to be retrofitted to withstand the upward forces generated by the engaged restraints (Kawashima and Matsuzaki 2012). The impacts of hydraulic forces are shown in Figure C-7.

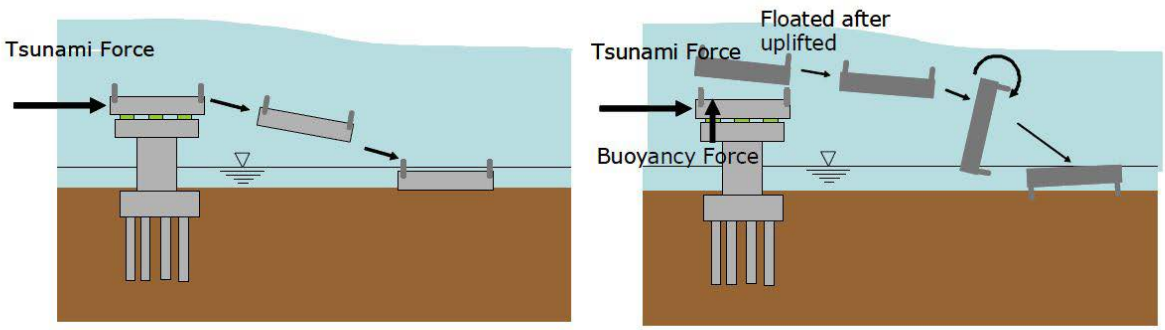


Figure C-7. Typical Tsunami Damage (Kawashima & Matsuzaki 2012)

C.2.6.5 Deep Foundations

Structures with deep foundations performed well in the tsunami. Scour of bents and abutments were not a major problem across the board, as these foundations are less vulnerable to scour. Most of the damage associated at these points was from the erosion of backfill (Kawashima 2011).

C.2.6.6 Fiber Reinforced Polymer

Fiber Reinforced Polymer (FRP) performed well in the earthquake and tsunami. Many bridges had been repaired and or retrofitted after previous earthquakes, and in most cases, hardly suffered damage in the 2011 earthquake.

C.3 Nisqually 2001 [Earthquake]

Table C-3. Nisqually Earthquake

Case Study Name/Date	Nisqually Earthquake (2001)
Location	Washington, USA
Event Type	Earthquake
Bridge Name	Alaskan Way Viaduct
Scope/Costs	Viaduct Replacement with Tunnel, estimated cost $3.1 billion
Planning Techniques/Tools	HAZUS and ShakeMaps
Event Response	Immediate inspections of nearby structures following the earthquake
Assessment Techniques/Tools	ShakeMaps in combination with bridge age, type, and period to identify which bridges are more likely to have suffered damage, as well as traditional visual inspection techniques
Rapid Restoration Type	Immediate temporary shoring, permanent replacement with a tunnel
Innovations	• Using bridge characteristics and seismic spectral acceleration to triage structures post-earthquake • Replacement of structure with tunnel instead of bridge

C.3.1 Introduction

In 2001, the Nisqually Earthquake startled the majority of Western Washington. The epicenter was about 18km NE of Olympia and 57km SW of Seattle. In total, 78 bridges were damaged, but the most alarming damage was located on the Alaskan Way Viaduct (Ranf et al. 2007; Farley 2018). The Viaduct was originally constructed in 1953 and was a prominent feature along the Seattle Waterfront. The extent of the damage was not discovered until months after the earthquake, igniting a fierce replacement campaign among researchers and engineers. Concerns about the bridge's structural integrity dated back to the Loma Prieta Earthquake in 1989, but it was not until the 2001 Nisqually Earthquake that steps were taken to address these concerns (Farley 2018). Figure C-8 shows the Viaduct prior to removal.

Figure C-8. Alaskan Way Viaduct (Washington State Department of Transportation 2020)

In addition to damage to the Alaskan Way Viaduct, researchers looked for a method to prioritize bridge inspections after the Nisqually Earthquake. Researchers determined that a combination of the spectral acceleration, year of construction, and bridge type were the factors needed to identify which bridges should be prioritized post-earthquake. These three factors correlated to the structures that had the most damage when compared to the map of actual damaged bridges, demonstrating the validity of this approach (Ranf et al. 2007).

C.3.1.1 Event Response

During the Nisqually Earthquake, inspectors were deployed based on epicentral distance and reports of observed damage. This required hundreds of bridges to be inspected immediately following the earthquake, using time, money, and resources. Post-earthquake, the value of pre-inspection triage was found, and researchers began developing ways to better categorize and determine the order of inspections (Ranf et al. 2007). Structures such as the Alaskan Way Viaduct were inspected at this time, however noticeable damage did not appear until months after the earthquake (Farley 2018).

C.3.2 Emergency Planning

In 1989, the Loma Prieta Earthquake in California caused the Cypress Freeway to collapse, a structure with a very similar design to the Alaskan Way Viaduct. This collapse worried many researchers at the time and led to an in-house review of the Viaduct. This review confirmed many similarities between the structures (Farley 2018). Moreover, the University of Washington conducted several seismic vulnerabilities studies in 1995 investigating the Viaduct to determine the limits of the structure during another seismic event, and up to what magnitude of earthquake the structure could withstand. However, these studies did not lead to major discussions on repairs or replacements until the 2001 Nisqually Earthquake (PB & Jacobs 2007).

C.3.2.1 Crowdsourcing and Information Gathering

To better understand the magnitude of the Nisqually Earthquake, researchers associated with the Pacific Northwest Seismograph Network (PNSN) studied information from ShakeMaps, a compilation of data from geologic statistics and strong-motion stations. In regions between data collecting sites, interpolation was used to fill in the map. During the Nisqually earthquake, 42 PNSN stations collected data on the earthquake, and this was used to generate the maps.

Another platform used for gathering information was HAZUS, a program which uses fragility relationships for a particular bridge based on span length, continuity, material type, and year built. HAZUS is used to analyze the probability of damage caused by an earthquake, and these likelihoods can be used to pre-plan which bridges should be inspected first, based on these characteristics. HAZUS models were used as a comparison to a prioritization method developed in a research project by the University of Washington. The project examined post-earthquake data from the Nisqually Earthquake to determine the viability of bridge characteristics-based structure prioritization to determine if the structures given a higher priority based on specific characteristics, such as type, age, and ground acceleration, matched with this pre-established system. Further discussion on the use of HAZUS and bridge prioritization can be found in the Innovations and Lessons Learned section (Ranf et al. 2007).

C.3.3 Assessment

The Alaskan Way Viaduct was initially inspected immediately following the Earthquake in February of 2001. During this inspection, there were no concerns about the bridge's structural integrity. However, in April of that same year, cracks were found near the structure's joints at the connections between the decks and columns, as shown in Figure C-9. These cracks were attributed to liquefaction of the surrounding soil. The inadequate soil below the bridge was estimated to be 30 feet deep in some regions, and consisted of lose soil, sawdust, and rubble. More alarming, the soil was held up by an aging wooden seawall. This discovery accelerated the need for a structure replacement, as the threat of the Cascadia Subduction Zone earthquake worried engineers (Farley 2018). An additional structural assessment was later conducted and found that the Nisqually Earthquake had weakened the connections between the columns and decks. Furthermore, it identified foundation problems due to shifting of the structure, which was compounded with cracks. The structure continued to shift even years after the earthquake. By 2009, the columns had settled an estimated 1.5 to 5.5 inches, depending on the location (Ott 2011).

Figure C-9. Cracks from Continued Column Settling (Lindblom 2014)

Additionally, the Washington DOT commissioned the Structural Sufficiency Review Committee (SSRC) to take another look at the Viaduct's structural integrity. The findings found that the structure would be severely damaged with return periods of only 108 years. This led to heightened efforts for total replacement (PB & Jacobs 2007).

C.3.4 Rapid Restoration

C.3.4.1 Contracting

After the Nisqually Earthquake, a replacement of the Alaskan Way Viaduct was determined to be the best option. The 2001 SSRC findings determined the seawall holding back the soil supporting the Viaduct and the structure of the Viaduct itself were prone to collapse in the event of another, especially larger, earthquake. This sparked the Alaskan Way Viaduct and Seawall Replacement Project (AWVSRP). Ideas ranged from a new viaduct, a tunnel, and a combination of both. Ultimately, a tunnel was decided on as the replacement option, as it was deemed to be safer than a new bridge with the threat of a major subduction zone earthquake (Figure C-10). Furthermore, other major cities had already taken similar action to demolish their existing elevated highways and saw benefits to other alternatives rather than replacing them with new elevated structures. Considerations toward the final decision also included impact to utilities, businesses, and motorists. The decision even went to the State of Washington Legislature. It was not until 2008 when the final tunnel decision was made after years of back and forth between key stakeholders (Ott 2011).

Figure C-10. Tunnel Construction (Washington State Department of Transportation 2020)

C.3.4.2 Design

The tunnel consisted of a deep-bore design hybrid. The estimated cost for the replacement was $300 million. The project was finally approved by the FHWA in 2011, and demolition started later that year (Ott 2011).

C.3.4.3 Temporary Structure

The Alaskan Way Viaduct was intermittently closed after the April 2001 discovery of cracks to install shoring and other temporary supports. As the structure continued to shift years after, WSDOT installed additional reinforcements in the columns and imposed weight limits on the bridge (Ott 2011). Examples of the temporary support deployed are shown in Figure C-11. These supports remained in place until the bridge was removed.

Figure C-11. Temporary Supports After Nisqually Earthquake (Photo by Erik Stuhaug, Courtesy Seattle Municipal Archives (113883))

C.3.4.4 Permanent Structure

Demolition of the Viaduct began in 2011 (Figure C-12) and was completed in 2019. The new double-deck tunnel totaled over 9200 feet in length. Tunnel boring operations began at the end of 2015 and continued until early 2017 (Ott 2011).

Figure C-12. Removal of Alaskan Way Viaduct (Washington State Department of Transportation 2018)

C.3.5 Challenges

With the Alaskan Way Viaduct, the liquefiable soil supporting the bridge created many challenges. The changes to the soil continued to create cracks in the structure years after the 2001 Nisqually Earthquake. Furthermore, the soil was supported by an aging seawall. The Viaduct was determined to be on “borrowed” time (Washington State Department of Transportation 2019).

Additionally, the decision to replace the structure with a tunnel was not easy. There were mixed opinions on what to do with the structure. Some environmental groups argued for the demolition without any replacement. A study was conducted with that scenario, and found that Seattle would be in gridlock, causing a full city shutdown. This idea was quickly vetoed despite pushes from the groups (Ott 2011). Despite these challenges, the removal of the iconic structure paved the way to a new Waterfront, as shown in Figure C-13.

Figure C-13. Before and After of Alaskan Way Viaduct Removal (Washington State Department of Transportation 2019)

Another challenge related to prioritizing bridge assessments after an earthquake. When considering bridge triage, it was unclear if bridge length or other characteristics correlated to bridge damage. Most of the structures damaged by the Nisqually Earthquake were approximately the same length, so it was not feasible to identify a correlation. Moreover, skew, type of span (continuous vs. simply supported) were not metrics considered at the time, and these could play a role with the likelihood of damage. There has not been a major earthquake in Washington since this metric was developed, so it is not possible to test the legitimacy of the fragility curves developed. However, researchers did apply these curves to smaller, less destructive earthquakes with positive results.

C.3.6 Innovations and Lessons Learned

C.3.6.1 Development of a Post-Earthquake Assessment Metric

Without developing a metric to decrease the total number of bridges that require immediate inspection post-earthquake, DOTs will be overwhelmed with the quantity of structures that need to be accessed. Furthermore, many of the bridges that are flagged for inspection based on this standard did not suffer any damage. Using a metric similar to the fragility curves developed can save time, money, and resources for the DOTs. Once initial inspections are complete, the remaining bridges within the specified epicentral distance can then be inspected to identify any structures that may have been inaccurately categorized. Without another major earthquake to test this metric, it is difficult to determine the validity of the system, but comparisons to smaller earthquakes have been promising, and this tactic should not be ruled out for future events.

For other structures in the Seattle area, data from ShakeMaps was used to find any correlation between the bridges that were damaged in the Nisqually Earthquake, as shown in Figure C-14. Generally, structures closest to the epicenter did have higher levels of damage, but bridges 30-45km away did not and ones 45-60km away did – the change in affected bridges did not directly correlate to distance. However, when the spectral acceleration was considered, the results became clear; structures located in the 0.3s spectral acceleration range had higher rates of damage. This correlation makes sense, as most of the bridges damaged were shorter in length and had a period of about 0.3s. Thus, resonance was more likely to occur at the locations, and therefore, more damaged was incurred (Ranf et al. 2007).

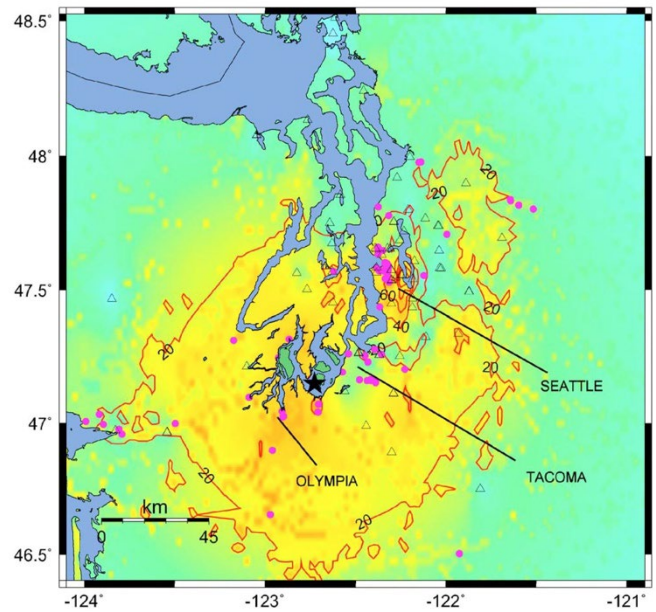


Figure C-14. ShakeMaps with Spectral Acceleration of 0.3s (Ranf et al. 2007)

Furthermore, the age of the bridge and the type of structure were found to correlate with damage. Movable bridges and trusses had the highest levels of damage. Structures built after 1975 performed much better, which is linked to the addition of seismic code provisions after the San Fernando Earthquake in 1971 (Ranf et al. 2007).

The actual performance of bridges during the Nisqually earthquake were compared to the HAZUS predictions, and the results varied with no strong correlation. In fact, HAZUS grossly overestimated the damage for some categories while underestimating others. New fragility curves were developed based on the Nisqually Earthquake data, which were more accurate compared to the HAZUS fragility curves. The new curves are thought to better represent the geologic conditions of the Pacific Northwest (Ranf et al. 2007).

C.3.6.2 Replacement Does Not Always Mean Bridge

The decision to replace the Alaskan Way Viaduct with a tunnel had broad ranging implications. With rapidly growing metropolitan areas, real estate prices have risen rapidly, and uses for the remaining parcels are targeted for building developments, rather than expanding transportation systems. The use of tunnels is a growing idea for crowded cities, and provides safer alternatives to bridges, especially in high-seismic areas. Tunnels are more flexible and can move with the ground motions. Although time consuming and expensive, tunnels can be a viable alternative to traditional bridge designs (Washington State Department of Transportation 2019).

C.4 Northridge 1994 [Earthquake]

Table C-4. Northridge Earthquake

Case Study Name/Date	Northridge Earthquake (1994)
Location	California, USA
Event Type	Earthquake
Bridge Name	No specific bridge selected for this Case Study
Scope/Costs	6 bridges failed and 4 replaced
Planning Techniques/Tools	HAZUS Prediction Models
Event Response	N/A
Assessment Techniques/Tools	HAZUS and REDARS
Rapid Restoration Type	CFRP and GFRP column and wall jacketing
Innovations	• Visual Assessment Catalog, HAZUS, and REDARS • Inspection team training • Emergency Contracts before event • Importance of retrofits

C.4.1 Introduction

On January 17th, 1994, the Northridge Earthquake reached a magnitude of 6.7 on the Richter scale near the San Fernando Valley in California. The initial shock lasted nly twenty seconds, but the damage to infrastructure resulted in the deaths of fifty-seven people (Cooper 1994). Out of the 2,000 bridges near the epicenter, six failed and four were so heavily damaged they had to be replaced (Alipour 2016). Figure C-15 shows an example of damage caused by the earthquake.

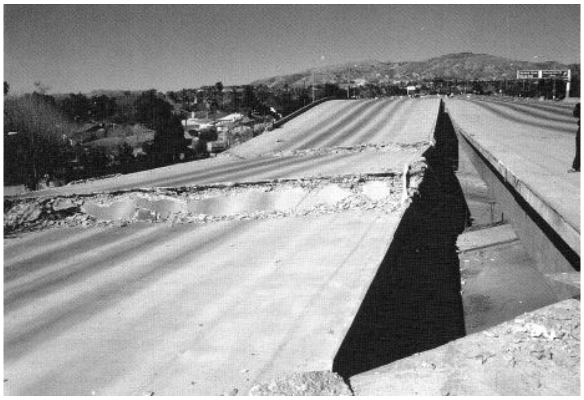


Figure C-15. Collapsed Elevated Freeway Caused by Northridge Earthquake (Buckle 1994, Photos courtesy of NCREER/MCEER Reports with support from the Federal Government via NSF)

C.4.1.1 Event Response

In response to the Northridge Earthquake in 1994, the California Department of Transportation (Caltrans) mobilized three teams of bridge inspectors immediately following the earthquake. These three teams of inspectors were specially trained in bridge assessment and were on the ground within three days following the event. The urgency in assessing and categorizing bridge damage contributed to the rapid response and repair of bridges following the Northridge Earthquake (Caltrans 2001).

C.4.2 Emergency Planning

C.4.2.1 Crowdsourcing and Information Gathering

Much of the crowdsourcing data related to this event is outdated due to the amount of time passed since the event occurred. The information gathering techniques were thus not explored for this Case Study.

C.4.3 Assessment

A few hours following the earthquake, three Post Earthquake Investigation Teams (PEQITs) were sent off to investigate the damages caused by the Northridge Earthquake. One team was assigned the Santa Monica Freeway, I-10, another the 118/405 interchange in Orange County, and the third to the Gavin Canyon Undercrossing collapse and 14/5 interchange. Overall, these three teams completed forty bridge inspections over the course of five days.

Typical damage from the Northridge earthquake included spalling and cracking of concrete abutments, settlement of approach slabs, tipping, or displacement of bearings, and spalling of column concrete cover, as shown in Figure C-16. Most of the bridges impacted were built before 1971 when more stringent bridge seismic standards were introduced, but some bridges built after 1971 also experienced minor damage. Bridge structures in Northridge built after 1971 with more stringent seismic standards experienced minor damage that was easily repaired (Cooper 1994). Assessment of bridge damage determined that the level of damage was found to correlate with bridge skew, abutment and pier type, and span continuity. Moreover, reinforced concrete bridges saw the most damage overall, many of which had short columns with limited amounts of transverse steel leading to shear failures (Marsh et al. 2013).

Figure C-16. Typical Column Spalling Damage (Marsh & Stringer 2013)

Ground motions for these sites were gathered from the California Strong Motion Instrumentation Program field sensors to better understand the seismic loads caused by the earthquake. Program estimations determined that 1,600 bridges experienced significant damage from the Northridge Earthquake based on the ground motion data. Sixty of these identified bridges had recently been retrofitted following the 1987 Whittier Earthquake. Bridges that had been retrofitted using hinge or joint restrainers and column jackets performed well in the earthquake (Cooper 1994). The bridges that had not been retrofitted experienced the most damage, and in some cases, collapsed. Bridges retrofitted with restrainers, even though they did not meet current standards, avoided severe damage, and performed quite well (Warrick et al. 1996).

C.4.4 Rapid Restoration

C.4.4.1 Permanent Structure

In response to the earthquake event, the first step to restoring damaged bridges in Northridge consisted of identifying and ranking bridges in order of retrofit priority. To repair existing bridges with damaged columns, the seat width of the columns and piers were extended, or cable restrainers were added across the joints. Additionally, old or inadequate bearings were replaced, and expansion joints eliminated. Restoration practices also involved footing overlays or extensions of footing retrofits, strengthening of cap beams, utilization of various isolation technology, and when possible, the use of single, continuous span rather than multiple simple spans (Cooper et al. 1994).

Restoration practices implemented following the Northridge Earthquake included jacketing damaged columns and filling cracks. Full height carbon and glass fiber reinforced polymer (CFRP & GFRP) wraps were used to jacket reinforced concrete columns. Damaged concrete was repaired using high strength mortar and lap-welding of fractured reinforcements took place in the plastic hinge region. Open diagonal cracks were filled with epoxy injections throughout the ports through the jackets. CFRP strips were placed at the wall edges to improve shear and flexural capacity of existing bridges following the earthquake. GFRP jackets were also used to wrap walls as a retrofit technique on Northridge bridges following the earthquake (Saini et al. 2013). Caltrans engineers faced a variety of damage types when assessing and repairing bridges affected by the Northridge Earthquake, as shown in Figure C-17.

Figure C-17. Severe Concrete Loss of Column and Reinforcement Buckling (Buckle 1994, Photos courtesy of NCREER/MCEER Reports with support from the Federal Government via NSF)

C.4.5 Challenges

Bridges with high skews and atypical geometries experienced greater levels of damage and did not perform consistently across the board. Caltrans bridge engineers had difficulty developing blanket repair methods or design retrofits that work across multiple bridge types (Cooper 1994).

Older bridges built during the 1970s also had mixed performance reviews. This was because newer seismic standards were just starting to be implemented, and it took about a decade of adjustments before designs showed dramatic improvements. Due to the variation in bridge design and performance over time, it is difficult to implement a one-size-fits-all repair method, and engineers had to develop unique solutions for each damaged bridge (Cooper 1994).

C.4.6 Innovations and Lessons Learned

C.4.6.1 General Design Findings

From the Northridge Earthquake, Caltrans bridge engineers learned that abutment fill failure often leads to approach slab failure. Inadequate lengths of abutment seats caused girders and slabs to fail. Excessive shear or flexural demands, often caused by poor confinement or detailing, leads to column failure. Excessive shear or flexural demands caused footing failures. Ground failures were due to uncontrollable liquefaction (Alipour 2016).

C.4.6.2 Emergency Contracts

Caltrans has emergency contracts already established, so when the Northridge Earthquake hit, contractors could respond immediately, and were already equipped with the tools necessary for inspections and identification of route detours. A heightened level of preparedness as demonstrated by Caltrans following the Northridge Earthquake has expressed benefits such as reduced cost, increased road user satisfaction, and more immediate response techniques to bridge assessment and restoration.

C.4.6.3 Base Isolation

Base Isolation and energy absorbing technologies may have been a beneficial method of building resilience into bridges affected by the Northridge Earthquake. Base isolation and other energy absorbing technologies perform excellently in buildings, but knowledge of their application on bridges is not widespread. Further investigation on the effectiveness of base isolation and energy absorbing technology should be performed as a potentially promising method of preparation for future earthquakes (Cooper 1994).

C.4.6.4 Post-Earthquake Inspection Team Training

One of the best methods to prepare for a disaster is to train teams of inspectors on how to evaluate bridges following an earthquake. Caltrans used two-person inspection teams made up of a bridge engineer and maintenance engineer to assess damaged bridges in response to the Northridge Earthquake. The team was responsible for determining if the bridge was safe to open (if closed) and which ones needed additional inspections to further assess the extent of the damage before re-opening (Cooper 1994). Furthermore, municipalities can improve earthquake response efforts by regularly training all emergency responders in the case of earthquake events (Marsh et al. 2013).

C.4.6.5 Visual Bridge Catalogs, HAZUS Models, and REDARS

Following the Northridge Earthquake, government officials, Caltrans, and emergency response planners, developed mitigation response plans by mobilizing inspection teams to assess the damage to bridges. Having a database of bridge conditions and bridge component capacities prior to the earthquake helps streamline earthquake response by mobilizing the PEQIT in order of bridge damage priority. After the Northridge earthquake, Caltrans implemented the Visual Bridge Catalog. The Visual Bridge catalog is used to categorize bridges according to failure mechanism, the shape of the hysteretic backbone (ductile, strength degrading, or brittle), and the damage level. This catalog has over one hundred reinforced concrete bridge references tested in the lab setting. Moreover, the Visual Bridge Catalog can be used to assess the damage to bridges within the epicentral region of an earthquake. The Visual Bridge Catalog contains specifications on over one hundred reinforced concrete columns involved in lab tests. The ability to assess and categorize by level of damage, and identify the failure mechanism, can help streamline the prioritization process post-seismic event (Marsh et al. 2013).

Another tool developed out of the Northridge Earthquake is HAZUS. HAZUS is a prediction model which aids in predicting the number of casualties and serious injuries following future earthquakes (Marsh et al. 2013). HAZUS is used in pre-disaster planning as it analyses data related to the physical condition of the bridges and roadways in normal conditions. HAZUS uses Geographic Information Systems (GIS) to geographically locate areas of high-risk which, in the event of a disaster, would have physical, economic, and social impacts on regions affected by the event. Caltrans determined this information would be beneficial to further develop prioritize structures for inspection and focus on retrofit efforts (FEMA 2020). HAZUS models can be used to visualize spatial relationships between the population and geographic assets such as the Santa Monica Freeway, the Gavin Canyon Undercrossing, and the 14/5 interchange, allowing bridge engineers to quickly identify and categorize bridges by damage level and type. With this information, Caltrans emergency response crews can conduct traffic along routes of bridge infrastructure with adequate capacity to handle the flow following an earthquake, while rapidly restoring bridges of the highest priority.

Another impactful tool available is REDARS software. REDARS analyzes road user losses relevant to traffic and roadway systems, as can serve as a helpful earthquake hazard mitigation tool. REDARS considers highway redundancies, traffic capacities, and the links between interstates and arterial roads. Caltrans found that software such as REDARS can aid in modeling the extent, type, and location of damage, allowing emergency response teams to determine the traffic volume capability of each bridge throughout the duration of the bridge restoration process. In addition to modeling time-dependent traffic capabilities, REDARS accounts for costs and downtimes needed for bridge repairs, which can help with the bidding process (Marsh et al. 2013).

C.4.6.6 Fiber Composite Retrofits as Preventative Measures

In preparation of future earthquakes, fiber composite retrofits should be used on bridge columns. The Northridge Earthquake was an excellent example of the improved performance of bridge columns which have been retrofitted with fiber composite materials such as CFRP strips and GRFP jackets (Buckle 2006).

C.5 Highway 54 over Sanders Creek Bridge 2018 [Flood]

Table C-5. Highway 54 over Sanders Creek Bridge Flood

Case Study Name/Date	Highway 54 over Sanders Creek Bridge Flood (2018)
Location	Arkansas, USA
Event Type	Flood
Bridge Name	Highway 54 over Sanders Creek Bridge
Scope/Costs	Replacement of Damaged Bent, cost N/A
Planning Techniques/Tools	N/A
Event Response	Bridge closure
Assessment Techniques/Tools	N/A
Rapid Restoration Type	Replacement of crushed bent
Innovations	• Purchasing materials from Federal Supply Surplus • Bailey Bridge Jack System

C.5.1 Introduction

This Case Study was developed based on the information provided by Arkansas Department of Transportation (ARDOT) in the Questionnaire. The information was supplemented by media sourced by Rusley 2018.

2018 Flooding in Arkansas led to the Highway 54 over Sanders Creek Bridge to be impacted by a large chunk of floating debris. A combination of debris impact and pile deterioration crushed the wooden intermediate bent, causing the bridge to sink (Figure C-18). Fortunately, the highway travel volumes were low, and the detour was short. Because of this, ARDOT was able to cultivate a newer method of repair with a Bailey Bridge system to jack up the bridge, allowing for the rapid replacement of the bent.

Figure C-18. Debris Damaged Columns (Courtesy of Heavy Bridge Maintenance, ARDOT)

C.5.1.1 Event Response

Immediately following the crushing of the timber bents, the structure was closed. It remained closed until the repairs could be completed in a couple of weeks.

C.5.2 Emergency Planning

No planning information was available.

C.5.3 Assessment

No assessment information was available.

C.5.4 Rapid Restoration

C.5.4.1 Permanent Structure

To repair the bridge, the sinking superstructure had to be lifted. This was accomplished by creating saddles to lift the bent cap with Bailey trusses equipped with jacks. From here, the crushed timber piles were able to be removed, and new piles could be installed. To place the Bailey Bridge truss, heavy-duty casters were bought, and brackets were built to connect the Bailey Bridge to the casters. Then the crew pushed the trusses into position and boom trucks on each side of the bridge approach were used to lift the Bailey Bridge into place (Figure C-19).

Figure C-19. Permanent Restoration (Courtesy of Heavy Bridge Maintenance, ARDOT) (A) Preparation for Jacking (B) Jacking System in Place (C) Launching of Bailey Bridge (D) Bailey Bridge Installed Across the Structure

C.5.5 Challenges

The crushed bent prevented any heavy equipment from being placed on the bridge. The design had to include the installation of a temporary span to help lift the sinking bridge, which included launching the spans from the river approaches.

C.5.6 Innovations and Lessons Learned

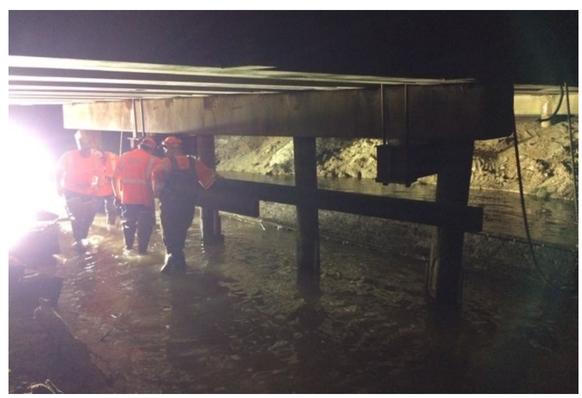
C.5.6.1 Purchasing of Supplies from Federal Surplus

The casters and other supplies used for this project were purchased at the Federal Surplus (Figure C-20A). The Arkansas DOT found this was a great resource to take advantage of. The DOT highly recommends it to other transportation agencies for quality materials and equipment for a low price.

C.5.6.2 Bailey Bridge Jack System

Typically, Bailey Bridges are used as temporary structures to reopen a structure. However, for this project, the system was used to lift the cap along with the superstructure off its crushed piles to replace the bent (Figure C-20B). This creative solution solved the problem of lifting the structure off the crushed piles without requiring heavy equipment on the structure. The Arkansas DOT had previously used a Bailey Bridge truss to pick up a damaged superstructure beam, but this was the first application of lifting a cap beam.

A



B

Figure C-20. Innovations (Courtesy of Heavy Bridge Maintenance, ARDOT) (A) Installation of Casters (B) Replacing the Bent

C.6 Michigan 2020 [Flood]

Table C-6. Michigan Floods

Case Study Name/Date	Michigan Floods (2020)
Location	Michigan, USA
Event Type	Flood
Bridge Name	US-10 Bridges over Sanford Lake
Scope/Costs	Twin bridges with extreme scour damage at abutments due to catastrophic dam failure causes flooding/total cost $1.78 Million
Planning Techniques/Tools	N/A
Event Response	Governor ordered Emergency Declaration, establishment of GIS platform for updates on construction and closures
Assessment Techniques/Tools	Visual assessment, underwater inspection, and drone footage
Rapid Restoration Type	Riprap, backfilling abutments
Innovations	• Interactive geographical information system (GIS) map • Governor Declaration of an Emergency Event • Design considerations for bridges located downstream of major dams

C.6.1 Introduction

The 2020 Michigan severe flooding was devastating to the Sanford Lake region. The flooding lead to the Edenville Dam failure on May 19th, 2020, and subsequent overflow of the Sanford Dam, draining their reservoirs and sending millions of gallons of water toward the cities of Midland, Edenville, and Sanford (Schafer 2020). The US Highway 10 Twin Bridges were caught in the wake, and extreme scour washed away part of their abutments. Michigan DOT officials noted they had never seen such extreme scour damage from one event (Heideman 2020). Drone footage and underwater inspections were used to assess the damage, and a combination of backfilling, replacing the bridge approaches, and adding scour countermeasures such as riprap are used to repair the structure and get traffic flowing again.

C.6.1.1 Event Response

Michigan Governor Gretchen Whitmer issued an emergency declaration on May 19th, which was quickly approved by President Trump. This permitted Michigan to use an emergency contracting approach to quickly secure a contractor for repairs (Lamb 2020).

In response to the floods, the Michigan DOT developed a GIS map to keep motorists updated on closures and construction. The platform also included photos from the different roadways and bridge job sites, including the US-10 bridges. Clear communication between the public and workers helped create a smooth repair process with limited disruptions (Schafer 2020).

C.6.2 Emergency Planning

C.6.2.1 Crowdsourcing and Information Gathering

Hundreds of videos were collected from eyewitnesses of the dam failure, rising river waters, and even the aftermath. Posts on different social media platforms were used to collect information on the impact and damage across the county (Chute 2020).

After the Dam failures, it was discovered the Edenville Dam had already multiple violations, most of them surrounding the inability of the dam to handle extreme floodwaters.

C.6.3 Assessment

A combination of visual inspections, drone footage, and underwater inspections were conducted to assess the situation. The underwater inspections (Browne et al. 2010) were heavily focused on the intermediate piers, as these did not have as much noticeable damage from the surface, and engineers wanted to be sure there was not extensive damage below the surface (Murdock 2020). The extent of the damage is shown in Figure C-21.

C.6.4 Rapid Restoration

C.6.4.1 Design

The eastbound bridge suffered less damage than the westbound, so repairs were started on this structure first. Construction on the eastbound bridge was completed by June 4th, which opened the bridge to one lane of traffic in each direction (Lamb 2020). To make this possible, a crossover system was first constructed to provide westbound traffic access to the eastbound bridge (Heideman 2020). On June 14th, the westbound bridge opened, restoring normal traffic patterns (Lamb 2020). The total cost of repairs totaled $1.78 million (Heideman 2020).

Figure C-21. Repairs to US-10 Bridge Approaches (Michigan Department of Transportation 2020)

C.6.4.2 Permanent Structure

To repair the region behind the abutment that washed away, the damaged bridge approaches were removed, and trees and other debris were carried off the bridge. Then, small rocks and sand were backfilled behind the abutment (Figure C-21). New approaches were poured, and scour countermeasures such as riprap was added. The riprap was made up of large rocks covering the abutments. The gap between the backfill and riprap was pressure grouted to secure the abutments (Murdock 2020).

C.6.5 Challenges

The biggest challenge with the repairs was the COVID-19 pandemic. Coordination of recovery efforts and repair plans needed to be developed with COVID restrictions in mind. However, some workers claim they were not provided with the essential personal protective equipment such as masks, were not required to wear masks on site, and were directed to perform tasks without regard for proper social distancing (Warikoo 2020).

C.6.6 Innovations

C.6.6.1 Geographic Information System (GIS)

During the major floods, MDOT developed an interactive GIS map for the public to use, informing them of closures and detours caused by the flood-damaged roads and bridge. Real-time updates and project photos were included on the map, establishing transparency with the public.

C.6.6.2 Declaration of an Emergency Event

Governor Gretchen Whitmer's declaration of an Emergency Event permitted the use of emergency contracts, which expedited the repair process. The ability to enact emergency protocols acknowledges the sense of urgency with the project and reduces the economic loss from the closures and detours, ultimately helping the community recover quicker.

C.6.6.3 Special Considerations for Bridges Downstream from Dams

Bridges located downstream of major dams should consider partial or full dam failure as part of their initial design or later retrofit. Examples of these precautions include extra protection for scour and severe flooding to reduce the likelihood of catastrophic failure.

C.7 I-69 Southbound Bridge 2017 [Hurricane]

Table C-7. I-69 Southbound Bridge Hurricane Harvey

Case Study Name/Date	I-69 Southbound Bridge Hurricane Harvey (2017)
Location	Texas, USA
Event Type	Hurricane
Bridge Name	I-69 Southbound Bridge
Scope/Costs	3 Bents repaired and 4 Spans replaced, estimated total cost $7.5 million
Planning Techniques/Tools	N/A
Event Response	Traffic rerouted to Northbound Bridge during construction
Assessment Techniques/Tools	• Fish Finder-like device • Visual Inspection • Acoustic Imaging
Rapid Restoration Type	Precast beams and panels
Innovations	• Incentives/disincentives for early completion or late finish

C.7.1 Introduction

Hurricane Harvey dumped over 19 trillion gallons of water over Texas in 2017. This massive quantity of water flooded cities and even changed the course of some rivers, like in the case of the San Jacinto River near Humble, TX. The San Jacinto River deepened, leading to extreme scour of the I-69 Southbound Bridge, as shown in Figure C-22. The structure was unable to carry typical freeway loads due to the unstable substructure, so it was closed after Hurricane Harvey for crews to remove and rebuild the scour damaged bents and their corresponding spans (Figure C-23). The $7.5 million project used precast concrete beams and panels, with equipment brought to the site via barge. The project was completed in 182 days, which was ahead of schedule (Tobia 2018). Overall, the repair was the largest bridge construction project following Hurricane Harvey (Poirier 2018).

Figure C-22. San Jacinto River Flooding Over I-69 (Kirk 2018)

Figure C-23. Scour Damage at Bent (Images courtesy of Padgett et al. 2018)

C.7.1.1 Event Response

While the Southbound Bridge was closed for construction, traffic was rerouted to the Northbound Bridge, which was reconfigured to accommodate traffic in both directions. This kept traffic flowing during repair and limited the disruption to commerce (Delaughter 2018).

C.7.2 Emergency Planning

No emergency planning information was available.

C.7.3 Assessment

The original I-69 Southbound Bridge was built in 1961. It was widened twice, once in 1982 and again in 1994. Eyewitnesses caught images of the bridge submerged under the San Jacinto River during Hurricane Harvey.

A few days after Hurricane Harvey, a reconnaissance team visited the I-69 Southbound Bridge and adjacent Northbound and Frontage Road structures. The team completed a visual inspection of the bridges, and found there was no visible pavement damage, however there were debris found pushed up against the structure and stuck on the adjacent Frontage Road Bridges. Moreover, scour holes were noted near the bents (Padgett et al. (2018)), as shown in Figure C-24. The research team recommended that all the structures needed additional inspections and repairs to restore the structural capacity and prevent future damage in future flooding or hurricane events (Padgett et al. 2018).

The Texas DOT used a SHIFLO, which is a fish finder device mounted on a ski. This device was used to measure the channel depth to determine the extent of the scour. Additionally, acoustic imaging was used to confirm the scour damage observed with visual assessments and the fish finder (Questionnaire). It was later determined the southbound bridge would not collapse, but had a substantially reduced load capacity, which led to the bridge remaining open with a new load posting. After plans for repair were developed, the bridge was closed, and construction began (Tobia 2018).

C.7.4 Rapid Restoration

C.7.4.1 Contracting

The estimated overall total cost for the project was $7.5 million. To incentivize early completion, crews worked 24/7 with early incentive and late disincentives. Two major project milestone were used to track progress (Poirier 2018). The incentive bonus was $500,000 for early completion (Begley 2018).

C.7.4.2 Design

To reduce the likelihood of damage from future flooding and hurricane events, the bridge’s foundational footprint was reduced to match that of the adjacent structures. This was accomplished by installing a new foundation. Drilled shafts were used as part of the new foundation (Poirier 2018). To expedite the repair process, the design also included the replacement of the spans above the new foundation repairs (Questionnaire).

C.7.4.3 Permanent Structure

To start repairs, the southbound bridge was closed, and traffic was rerouted to the northbound side. After demolition, the new foundation was built with drilled shafts, which were designed to withstand scour. In total, 3 bents were removed and 4 spans (Poirier 2018). All construction was completed by equipment placed on barges, as shown in Figure C-25 and Figure C-26. Precast deck panels and beams were used, speeding up the actual construction process. Traditioanl construction methods were used in tandem with the precast elements for a faster repair (questionnaire).

Figure C-24. Damage Observed (**Images courtesy of Padgett et al. (2018)**) (A) Scour Along Column Bents (B) Debris Build-Up (C) Debris Trapped at Deck Level (D) Erosion Along Bank

C.7.5 Challenges

The damage to the southbound bridge impacted traffic, especially oversized vehicles. Due to the scour damage, the structure was unable to carry heavily loaded vehicles. However, this routine heavy-haul truck traffic was able to be rerouted to the adjacent frontage roads, as this crossing of the San Jacinto River has multiple bridges in a short area (Figure C-27). During the repairs, the disruption to traffic was also limited due to these adjacent structures, as traffic could easily be directed to the northbound bridge or the frontage roads.

Figure C-25. Crane Working from Barge (Google Maps 2018)

Figure C-26. Construction of New Spans (Tobia 2018)

C.7.6 Innovations and Lessons Learned

C.7.6.1 Span Replacement & Foundation Repair

The decision to replace the span directly above the foundation repair helped speed up the repair process. Without the replacement, it would have been extremely difficult to preserve the spans while installing the new drilled shafts. Even though it sounded like more work, removing the old span and having the open region for the construction helped expedite the entire process (questionnaire).

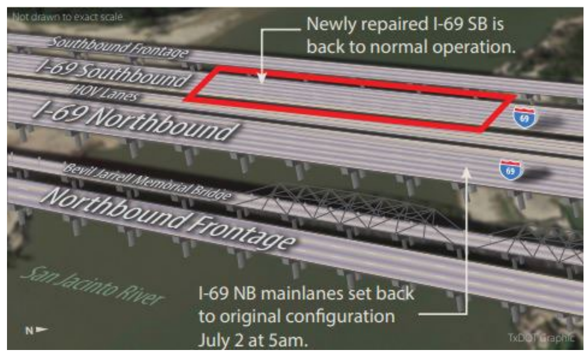


Figure C-27. Adjacent Structures (Texas Department of Transportation 2018)

C.8 Katrina 2005 [Hurricane]

Table C-8. Hurricane Katrina

Case Study Name/Date	Hurricane Katrina (2005)
Location	Louisiana, USA
Event Type	Hurricane
Bridge Name	I-10 Twin Bridges
Scope/Costs	54 Spans Collapsed into the water and 473 spans had shifted alignments, total repair cost $30 million, replacement $753 million
Planning Techniques/Tools	Seeking advice from other DOTs who experienced similar damaged bridges; group proposal development with bridge engineers, maintenance crews, and inspectors.
Event Response	Preliminary inspection completed 1 day after
Assessment Techniques/Tools	Comparisons to similar structures; lab tests
Rapid Restoration Type	Temporary repairs, later replacement
Innovations	• Repairing damaged spans to use with adjacent bridge to reopen bridge to traffic sooner • Considerations of buoyant forces with designs

C.8.1 Introduction

On August 29th, 2005, the Category-5 Hurricane Katrina hit much of the Gulf region of the United States. Hundreds of bridges suffered damage, including the Lake Pontchartrain I-10 Twin Bridges. The twin bridges had 54 collapsed spans and 473 misaligned spans caused by deck movement due to upward buoyant forces as shown in Figure C-28. A total cost of $30 million was estimated for the temporary structures and replacement. Since Interstate 10 is part of the National Defense Network, it was key to get the freeway up and running as soon as possible. Temporary repairs of both bridges were the focus, then once traffic was reopened, plans for twin replacement bridges were developed (Padgett et al. 2008).

Figure C-28. Aerial View of Damaged and Missing Spans (Alipour 2016)

Figure C-29. Map of Twin I-10 Bridges Region (Chen et al. 2007 with funding from USGS)

C.8.1.1 Event Response

A day after Hurricane Katrina hit, a team of LA DOTD inspectors made a preliminary inspection of the twin bridges. Additional inspections were conducted in the days and weeks that followed (Alipour 2016). Figure C-29 shows the surrounding area of the I-10 Twin Bridges.

C.8.2 Emergency Planning

C.8.2.2 Crowdsourcing and Information Gathering

The state of Florida suffered similar damage from with the I-10 Escambia Bridge from a previous hurricane. LA DOTD met with the Florida DOT to discuss key takeaways Florida had with their twin bridge repair, and what tools and equipment were needed (Alipour 2016).

C.8.3 Assessment

The I-10 Bridges were given the HAZUS damage category of “complete”, indicating collapse or connection loss at bearings causing deck collapse or substructure tilting. Despite a relatively low torm surge of 4.02 m, the damage was significant compared to other damaged bridges subject to similar surge heights (Padgett et al. 2008).

Figure C-30. Highway 11 Bridge Girder Opening (Chen et al. 2007 with funding from USGS)

It was noted that the higher spans toward the center of the lake’s navigation channel did not suffer the same levels of damage as the lower approach spans. This finding suggests that the cause for the bridge collapse was built-up hydrostatic pressure, which made it easier for the spans to float away. Lab tests were conducted with replica girders and found that if only 55% of the volume was filled with trapped air, the spans were able to float away. Using surge data, it is estimated the bridges experienced up to 70% of filled voids, significantly higher than the 55% threshold that would initiate floating spans. With this buoyancy, it would only take the slightest horizontal disturbance to shift the spans off the bents and cause the 50+ missing spans and hundreds of shifted spans. Furthermore, the adjacent Highway 11 bridge span did not experience the same damage as the I-10 Bridges. The design of the girders in the I-10 Bridges included holes through them to relieve the hydrostatic pressure build-up, as shown in Figure C-30. Further inland on the lake, a railroad bridge also did not experience the same damage, and that bridge’s design included solid deck slabs, which did not allow for any built-up hydrostatic pressure. These emprical findings imply that approriate surge-resisent bridge-span design is essential to water-crossing bridges in hurricane prone coastal regions.

C.8.4 Rapid Restoration

C.8.4.1 Contracting

Funding for the repairs, like most of the bridges damaged by Hurricane Katrina, were from FEMA or Emergency Response (ER) funds. After a plan was developed to repair the twin bridges, a pre-bid meeting was held with various contractors, bridge designers, and maintenance crews to develop a proposal for the project. Altogether, the team developed four phases for the project (Alipour 2016).

C.8.4.2 Temporary Structure

In Phase 1, spans from the westbound lanes were moved to fill in missing spans in the eastbound lanes using Self Propelled Modular Transporters (SPMT) on barges. Repairs were made to align the shifted spans, as shown in Figure C-31. This process took an estimated 45 days to complete, and the contractor was offered incentives/disincentives for early or delayed completion. With the eastbound lanes' temporary repairs, traffic was able to resume across the lake only 42 days after the Hurricane (Alipour 2016).

Figure C-31. Girders Fallen off Bent (Alipour 2016)

For Phase 2, the scavenged westbound bridge was replaced with prefab bridges (provided by the Acrow Bridges), which are a type of steel modular structure. With these temporary bridges installed, the westbound bridge was then reopened to traffic Alipour 2016).

Phase 3 included maintaining the repaired eastbound bridge and the Acrow westbound bridge until a total replacement (Alipour 2016).

C.8.4.3 Permanent Structure

In Phase 4, plans for the replacement bridge were developed and the new bridges were built (Alipour 2016). The new twin bridges use 36-inch precast piles for the substructure. The two bridges carry 3 lanes in total with 12-foot-wide shoulders. At midspan of the bridges, the structure rises to accommodate the passing ship traffic. To reduce the threat of ship impact, pile supported waterline footings were installed near the ship navigation channel (Massman Construction Company 2020). The replacement cost of $753 million, and was fully funded by the FHWA, and included specifications on traffic maintenance, right-of-way, and the environment with the design. Construction included three phases, with phase 1 including the substruction erection, phase 2 included the concrete spans, and phase 3 the navigation channel. Two design-bid-build contracts were used, one for phases 1 and 2, and the other for phase 3. Other considerations included a 100-year service life, storm and collision impact resistance, and a rapid completion. The bent placement was designed to maximize the span lengths to reduce the number of required intermediate supports. The twin bridges used prefabricated concrete piles, bent caps, girders, and stay-in-place forms for the pile footings (D'Andrea 2011).

The pile design took large moment capacities into consideration for storm and impact resistance. To connect to the precast bent, a concrete moment plug was used, and depending on the location of the bent, extended 30 feet. Some are even designed to resist uplift caused by buoyant forces. For the footings, construction was made easier by setting their elevation above the high-water level. The girders were designed for maximum length and spacing, permitting the use of larger prestressing forces. By using barges to transport materials to the site, the contractor did not have to worry about the shipment of the large girders. A continuous cast-in-place deck was poured on top, reducing the number of joints. Once the new structures were built, the existing bridges were torn down, and the materials salvage were used to line the shoreline, creating reefs for native fish (D'Andrea 2011).

C.8.5 Challenges

The biggest driving factor for this project was time. It was determined the best course of action was to start with the temporary repair of opening on bridge to traffic, then focus on the permanent replacement structures in the future. This decision allowed for more time with the permanent structure design and gave the opportunity for the state to investigate different funding sources.

C.8.6 Innovations and Lessons Learned

C.8.6.1 Use of GIS Database for Prediction Models

To better prepare for the next Hurricane, the LA DOTD developed a wave/surge atlas. Using 100-year design storm data, a GIS database was established to identify the brides at risk and used bridge characteristics such as weight to locate the most vulnerable span(s) on the entire bridge. With funding, these bridges could then be retrofitted to better prepare for a major disaster or indicate where inspections should start after a storm surge or hurricane (Alipour 2016).

C.8.6.2 Considering Buoyant Forces in Hurricane Bridge Design

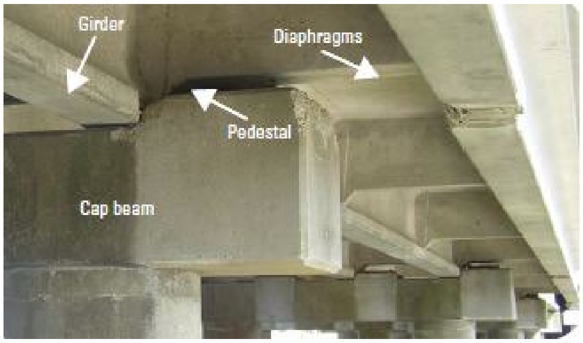


Figure C-32. Girder Design Creating Trapped Air (Chen et al. 2007 with funding from USGS)

During a hurricane or major flooding event, damage might not be from the common causes such as debris impact or scour, but from the buoyant forces on the bridges. Bridges are not always designed for uplift, and they should be designed to not trap air under the deck or in the superstructure to provide some relief to these forces. Figure C-32 highlights this flawed design. Additionally, bridges seismicity-inactive regions are not always designed to dynamic forces in mind, and this can cause issues during dynamic moving of water. Static designs should still be used, but dynamic forces should also be considered for water-crossing bridges subject to extreme flood or surge events. To consider dynamic lateral loadings from water, the shear keys should be installed to hold girders in place (Robertson et al. 2007).

C.9 I-95 Chester Creek Bridge 1998 [Fire]

Table C-9. I-95 Chester Creek Bridge

Case Study Name/Date	I-95 Chester Creek Bridge (1998)
Location	Pennsylvania, USA
Event Type	Fire
Bridge Name	I-95 Chester Creek Bridge
Scope/Costs	All three southbound lanes for a total cost of $4 million
Planning Techniques/Tools	Expedited emergency contracting procedures
Event Response	Modification of traffic flow on the northbound lanes to accommodate southbound traffic as well.
Assessment Techniques/Tools	Visual Inspection
Rapid Restoration Type	Temporary lane additions; replacement of nine girders, deck section repairs, and bent repairs.
Innovations	• Active involvement of state leadership (i.e., Governor, PennDOT Chief Construction Engineer) streamlined the approval process and expedited the response and repair • Easily accessible existing design plans, design calculations, and shop drawings

C.9.1 Introduction

The Chester Creek Bridge was built in 1965, with a three-span continuous steel girder design and a concrete deck. The substructure was composed of concrete bents. On May 23rd, 1998, a gasoline tanker truck collided with the I-95 Chester Creek Bridge center median, flipping over the barrier, and crossing traffic on the southbound lanes. The truck impacted another vehicle and spilled 8700 gallons of fuel, which burst into flames. The southbound lanes of the bridge experienced severe damage from the fire (The Washington Post 1998). Engineers decided to replace the damaged portions with an identical structure, for a total cost of $4 million, as shown in Figure C-33 (Bai and Burkett 2006).

Figure C-33. Placement of New Girders (Bai and Kim 2007)

C.9.1.1 Event Response

Immediately following the crash, the Pennsylvania Department of Transportation (PennDOT) closed both directions of traffic to maintain the public’s safety until the structure could be assessed by bridge engineers (Bai, Burkett, and Nash 2006). After assessing the bridge, engineers determined the southbound lanes were unable to carry any traffic loads due to the fire damage. Instead of using a long-term lengthy detour route, they decided to modify the traffic flow of the unaffected northbound lanes to carry traffic from both north and south directions (Bai, Burkett, and Nash 2006).

The temporary lane construction started the same day as the event. Over 200 laborers worked through the night and removed over 140 feet of concrete median barriers to build the crossovers (Bai, Burkett, and Nash 2006). The three northbound lanes were narrowed to eleven feet, and an additional lane was added. Two lanes were used for northbound and two for southbound traffic. A 40mph speed limit was also imposed during construction, and this was patrolled by State Police for worker and driver safety (Bai and Kim 2007).

C.9.2 Emergency Planning

No information was available for emergency planning information after the event.

C.9.3 Assessment

Bridge engineers from PennDOT arrived on scene as soon as was possible to complete visual assessments of the bridge. They found nine girders were damaged on the southbound lanes, and portions of the concrete deck and a segment of one of the concrete bents needed to be repaired. In total, 2/3 of the southbound superstructure was deemed unsafe and required replacement (Bai, Burkett, and Nash 2006).

C.9.4 Rapid Restoration

C.9.4.1 Contracting

To avoid a lengthy bidding process, the Governor of Pennsylvania declared the fire a state emergency. This permitted PennDOT to expedite the entire repair process, as it allowed them to forgo typical procedures and regulations. PennDOT was able to hire, purchase, and contract with the firm of their choosing. The secretary of PennDOT selected the same contractor who built the original structure. The firm was paid on a time and materials basis. Mark-ups for prices corresponding to previous PennDOT standards were also used, along with incentives/disincentives for project milestones. All contracting and general procedures followed PennDOT's previously established PUB 408 document, which helped expedite the processes even further. PUB 408 is PennDOT's specifications manual which contains requires for construction and contracting procedures (Bai and Burkett 2006). The contractor was responsible for building the crossovers needed to create temporary lanes on the northbound side. Once this was completed, they repaired the damaged girders and deck (Bai, Burkett, and Nash 2006). The demolition of the damaged girders and deck was completed in tandem with material preparation.

C.9.4.2 Design

It was determined that the best option was to rebuild using the original design of the bridge, which included steel girders (Bai and Kim 2007). The original shop drawings of the girders were located by PennDOT and sent to the manufacturer. This accelerated the process as they did not have to reapprove the drawings. Updates to code and other standards were waived by PennDOT, as the original design was deemed 'sound' and followed proper engineering judgement. Furthermore, the time-based specifications for concrete maturity and bottom rebar ties were waived (Bai, Burkett, and Nash 2006).

C.9.4.3 Procurement

Typically, the steel manufacturer would take upwards of 3-4 weeks to complete a similar project, but the fabricator worked in 24 hour shifts to complete the order in 10 days. The fabricator constructed nine, 65-80' long girder segments. Each were 6'-8" tall and weighed 15-20 tons. To assist the fabricator and speed up the manufacturing process, PennDOT changed their routine procedures and conducted the required inspections at the steel plant and at the fabrication shop (Bai and Kim 2007).

C.9.4.4 Permanent Structure

To transport the new girders to the site, the Governor of Pennsylvania issued a permit to allow the manufacturer to transport three girders at a time. Under normal Commonwealth law, the size of the girders restricted loads to only one at a time (Bai, Burkett, and Nash 2006).

Figure C-34. Curing of New Deck (Bai, Burkett and Nash 2006)

After setting the girders in place, steel deck pans were set between them. Then, reinforcing bars were installed, and the 10in thick deck was poured, as shown in Figure C-34. Once the deck was cured, two lanes were moved back to the southbound side for a partial reopening on June 25th. From this point, new concrete barriers were added to replace the old median and the rest of the lanes were open to traffic. Repair work on the minor-damaged bent continued until July 3rd, which was 12 days ahead of schedule. The total cost of the project was $4 million, and the contractor received $500,000 in overtime pay (Bai, Burkett, and Nash 2006).

Date	Events
05/23/98	Accident occurred
05/23/98	PennDOT awarded repair contract to Buckley & Company, Inc.
05/24/98	Two temporary lanes in each direction opened to traveling public.
05/24/98	Buckley awarded steel girder fabrication to High Steel Structure, Inc.
05/26/98	High Steel ordered steel material from Bethlehem Steel.
05/29/98	High Steel started to receive steel plates.
05/29/98 to 06/02/98	Demolition of 16-m-wide concrete deck.
06/03/98 to 06/04/98	Removal of nine sections of fire-damaged steel girders.
06/07/98	Fabrication of nine girder segments was completed.
06/08/98 to 06/09/98	Buckley installed steel girders.
06/16/98	New 254 mm concrete deck was poured.
06/25/98	PennDOT moved two lanes of traffic back to southbound I-95.
06/27/98	Interstate Safety Services delivered 854 m concrete road median.
06/28/98	Installed concrete road median and marked traffic lanes.
06/29/98	Bridge was reopened and traffic was restored.
07/03/98	Entire repair work finished, 12 days ahead of original schedule.

Figure C-35. Timeline of Project (Bai, Burkett, and Nash 2006)

C.9.5 Challenges

The extreme event occurred over Memorial Day weekend, which is one of the busiest travel weekends in the nation. On a normal day, 80,000 vehicles crossed the Chester Creek Bridge, so traffic impacts were significant before the temporary lanes could open (Bai, Burkett, and Nash 2006).

During this expedited process, the competitive bid procedure was omitted, and this was considered unfair by other companies. To create equal opportunity and maintain a short bidding process, DOTs should have the capability to rapidly create emergency bidding packages and use standby emergency contracts. Developing emergency procedures and protocols to aid in this response can help future projects (Bai, Burkett, and Nash 2006).

Lastly, it was difficult to estimate how long it would take for the project to be completed. The project finished twelve days ahead of schedule, so the original estimates were conservative. Better logging of progress and productivity can be used in the future for other DOTs to make better estimates of project duration, which can have a major impact on repair methods, detours, and temporary structure use (Bai, Burkett, and Nash 2006). Figure C-35 shows the final timeline for the project.

C.9.6 Innovations and Lessons Learned

C.9.6.1 Governor Declaration of a State of Emergency

Using the power of the state Governor was vital to the rapid restoration of this project. From the declaration a state of emergency, to issuing special permits for material transport, the Governor of Pennsylvania played a large roll into this project's success (Bai, Burkett, and Nash 2006).

C.9.6.2 Chief Construction Engineer Availability

The PennDOT Chief Construction Engineer was always on site. This prevented the need of a formal request or submission for anything that came up during construction and provided another point of contact for asking questions (Bai, Burkett, and Nash 2006).

C.9.6.3 Pre-established Contracts

Using established contacts and procedures for emergency situations can help expedite the contracting process, which can often be the lengthiest aspect of a project (Bai, Burkett, and Nash 2006).

C.9.6.4 Temporary Lane Construction

Temporary lane construction (or temporary structures if needed) is a very good way to keep traffic flowing. These need to be constructed as soon as possible to be most effective, as detours can cause a litany of problems for infrastructure that was not originally designed for that level of traffic. State Police or other law enforcement can help with traffic control and enforcement of reduced speed limits through work zones (Bai, Burkett, and Nash 2006).

C.9.6.5 Centralized Location for Maintaining Bridge Documents

A centralized location for storing previous bridge plans, design calculations, and inspections can really help with emergency inspections. Access to accurate and complete plans streamline the design process, and can even be reused, as they were in this case (Bai, Burkett, and Nash 2006).

C.9.6.6 Waiving Routine Design Procedures

Waiving certain contracting or design procedures can speed up the repair process. If existing plans are reused, new standards and rules can be waived if the original structure and design was deemed structurally sound (Bai, Burkett, and Nash 2006).

C.10 I-29NB Perry Creek Conduit 2019 [Fire]

Table C-10. I-29NB Perry Creek Conduit Fire

Case Study Name/Date	I-29NB Perry Creek Conduit Fire (2019)
Location	Iowa, USA
Event Type	Fire
Bridge Name	I-29NB Bridge over Perry Creek Conduit
Scope/Costs	5/8 heavily damaged beams led to total replacement; $1 million
Planning Techniques/Tools	N/A
Event Response	Reduced bridge capacity to 1 lane
Assessment Techniques/Tools	Visual assessment, hammer sounding
Rapid Restoration Type	Total replacement
Innovations	• Nondestructive tests not always required • Fire damage impacts structures of all ages

C.10.1 Introduction

Figure C-36. Fire Damage to I-29NB Perry Creek Conduit Bridge (Used with permission © Iowa Department of Transportation, HDR 2019)

This Case Study was developed based on the information provided by the Iowa Department of Transportation (IDOT) in the Questionnaire. The information was supplemented by media sourced by Deckert 2019, HDR 2019, Hytrek 2020, and Rennie 2020.

IDOT was almost finished with the 12-year long I-29 improvement project when a fire, caused by a homeless campfire, which ignited a nearby propane tank, causing an explosion, broke out under the I-29NB Perry Creek Conduit Bridge on October 30th, 2019 (Figure C-36). The single span bridge carried 3 northbound lanes of traffic and had been completed only a year before (Deckert 2019). 8 concrete beams made up the superstructure, and three interior girders suffered severe damage, and two with some damage because of the fire (HDR 2019). IDOT hoped the repair would take under a month, but a consultant investigation revealed the extensive damage to the interior girders – causing the structure to be ultimately replaced. Its completion marked the end of the I-29 improvement project (Deckert 2019 and Rennie 2020).

C.10.1.1 Event Response

Once the fire was put out, the air quality under the bridge was first verified by local fire crews to permit access to inspection teams. After a brief inspection, the bridge was soon reopened to one lane of traffic across the bridge (over the minorly damaged beams). Before the Iowa DOT could open a second lane, the structural capacity was tested with an in-house load rating (HDR 2019). During the replacement process, traffic was eventually rerouted to the southbound bridge, with two lanes in each direction (Hytrek 2020).

The bridge was also instrumented to gather deflection measurements during conducted load tests. These tests were performed by the Iowa State University Institute for Transportation Bridge Engineering Center (Phares et al. n.d.).

C.10.2 Emergency Planning

C.10.2.1 Crowdsourcing and Information Gathering

Fire damage is a relatively unknown aspect within bridge engineering. There are currently a lack of standards and guidance for how to plan and assess structures damaged by fire. However, fire does not occur as frequently as other types of emergency events, such as collisions, so many transportation agencies, such as Iowa, are not well-versed in planning of these situations. Figure C-37 shows the extent of the damage caused by the fire.

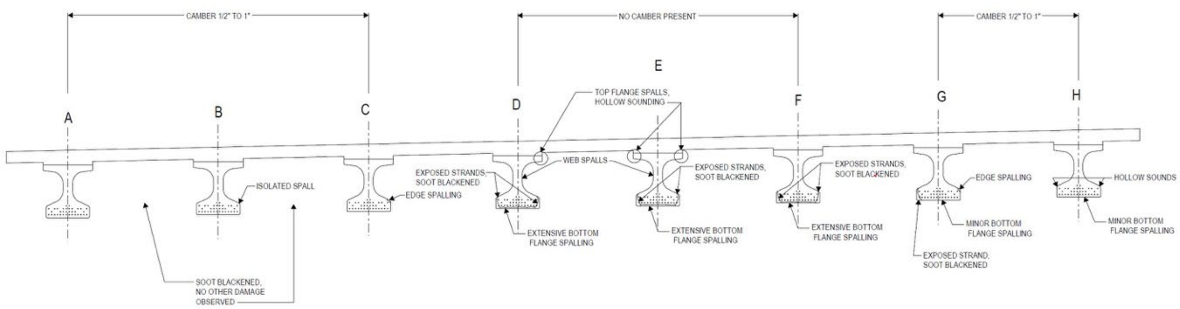
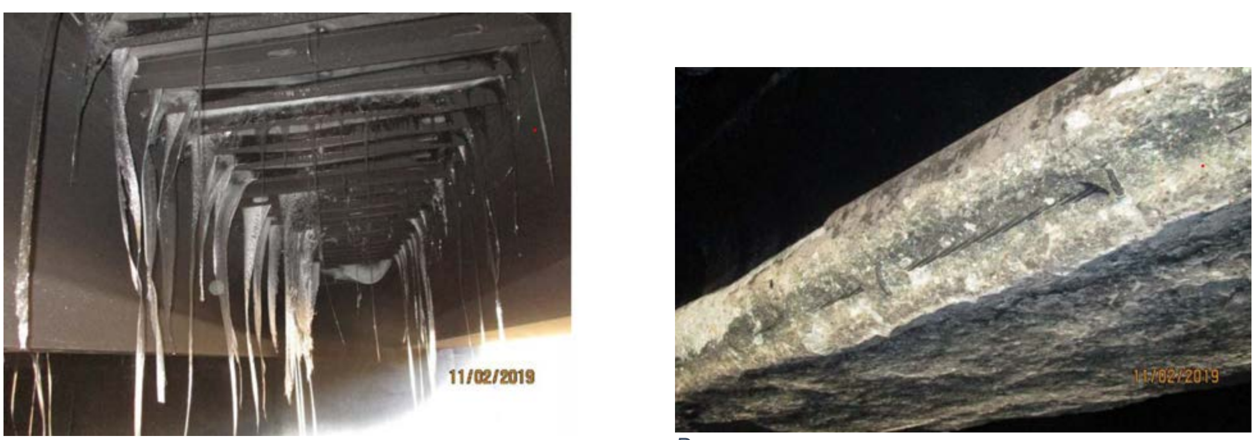


Figure C-37. CAD Drawing Showing Damaged Beams of the Bridge (Used with permission © Iowa Department of Transportation, HDR 2019)



A *B*

Figure C-38. Fire Damage (Used with permission © Iowa Department of Transportation, HDR 2019) (A) Stay-in-Place Construction Forms and Cross Bracing (B) Spalled Concrete

C.10.3 Assessment

The Iowa DOT hired a consultant to aid in the assessment of the fire damaged structure. To assess the damage caused by the fire, a visual inspection was first completed, followed by sounding of the concrete surfaces to check for delaminations. The visual assessment was used to investigate misalignment of the beams, sag, melting of cross supports, and a detailed look of the exposed prestressing and reinforcement strands (Figure C-38). Nondestructive testing was not conducted in the investigation. Petrographic testing was considered but was thought to be too time-consuming and not a viable option due to the layout with the beam flanges (HDR 2019).

The bridge was easily accessible from the ground, so only an electric light and a portable generator were required to help illuminate the inspection. Snoopers and other equipment were not needed (HDR 2019).

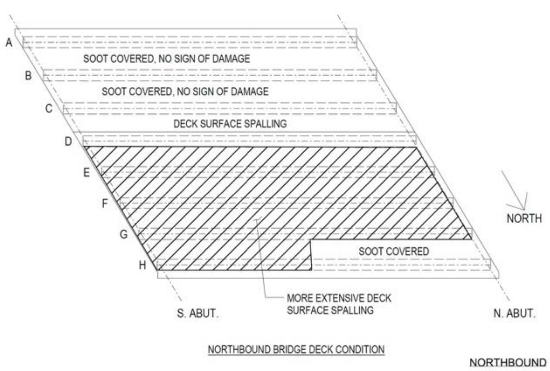
The inspection found severe spalling and delaminated concrete of 5 concrete beams, with noticeable remaining camber in lightly damaged beams. From these observations, the consultant recommended the Iowa DOT restricted traffic to the minorly damaged portions until the capacity of the heavily damaged region could be verified. Total replacement of all damaged beams was also recommended. The damage noted was determined to be caused by heat rather than blast and was mostly concentrated at the flange regions of the beams (HDR 2019). Lastly, the consultant recommended the bridge undergo a load rating to determine the remaining capacity in the heavily damaged beams, also with long-term structural monitoring (HDR 2019). Iowa DOT hired the Iowa State University Iowa State University Institute for Transportation Bridge Engineering Center to perform a series of field load tests. The bridge was instrumented with BDI strain gages long at midspan and quarter points along each girder. Six load case scenarios were tested, and a load distribution factor (DF) was calculated for each load case. The results indicated that 2 of the 8 girders had a DF greater than their original AASHTO design. These girders were the ones with the most visible damage and were located toward the middle of the bridge (Phares et al. n.d.). This information was also to make the restoration design decision.

C.10.4 Rapid Restoration

C.10.4.1 Permanent Structure

Most of the damage from the fire was located near the center of the bridge (Figure C-39A). Because of this location and the severity of the damage, it was determined a total replacement was the best option, as opposed to repairing the damaged beams, as shown in Figure C-39B (Hytrek 2020).

The original bridge, construction a year before, cost $800,000. However, the replacement after the fire totaled $1 million. The project started in March of 2020 and wrapped up in July (Rennie 2020).



A

B

Figure C-39. Permanent Structure (A) Plan View of Damaged Bridge Portions (Used with permission © Iowa Department of Transportation, HDR 2019) (B) Replacement of Bridge (Hytrek 2020)

C.10.5 Challenges

One of the challenges with the fire damage was the unknown impact on the bridge's remaining structural capacity. Bridges are not typically designed with fire resistance in mind, and even though the bridge was brand new, it still was highly susceptible to the high heat and blasts caused by the exploding propane tanks. Understanding the extent of the damage required IDOT to hire a consultant to assess the fire-related damages to help decide the fate of the structure.

Additionally, the fire took place right as the I-29 improvement project was wrapping up. Commuters and motorists were once again disrupted due to the restricted traffic flow across the bridge and other construction in the region. The fire did create a several-month setback and was frustrating to the public.

C.10.6 Innovations and Lessons Learned

C.10.6.1 Nondestructive Test not always Required

In the case of I-29NB Bridge's assessment, nondestructive tests were deemed unnecessarily. The extent of damage was able to be observed with a visual assessment only, and deflections and changes in camber were recorded. Nondestructive testing was not required to make a full observation of damage, and the best assessment came from a load rating of the bridge, which included the effects of the damaged members (HDR 2019).

C.10.6.2 Age of Bridge Not a Determinant of Fire Damage

The I-29NB Bridge had been completed only a year before the fire. Even with current design standards, the structure still required a total replacement. Often, bridge damage correlates to the age of the structure when it comes to other emergency events. However, even if the current engineering specifications, fire can leave a devastating impact, and effects structures of all ages.

C.11 Glenn Highway and Eagle River Overpass 2018 [Collision]

Table C-11. Glenn Highway and Eagle River Overpass Collision

Case Study Name/Date	Glenn Highway and Eagle River Overpass Collison (2018)
Location	Alaska, USA
Event Type	Collision
Bridge Name	Eagle River Overpass
Scope/Costs	Immediate Repairs \$1.5 million, Permanent Repairs \$1.5 million
Planning Techniques/Tools	N/A
Event Response	Full closure
Assessment Techniques/Tools	Visual assessment and unmanned aerial vehicles
Rapid Restoration Type	Girder removal, eventual replacement
Innovations	• Structural engineer on site • Temporary girder removal until replacement

C.11.1 Introduction

This Case Study was developed based on the information provided by the Alaska Department of Transportation & Public Facilities (Alaska DOT&PF) in the Questionnaire. The information was supplemented by media sourced by Levings and Murray 2019.

On March 21st, 2018, an overheight commercial vehicle struck a prestressed/post tensioned concrete girder on the South Eagle River Overpass on the Glenn Highway in Anchorage, Alaska. The damage was so severe, it caused the entire interstate interchange to be shutdown (Figure C-40). The design of the interchange created limited detour options, causing substantial traffic gridlock. The impact was so significant, many state offices and other businesses in Anchorage partially closed to help alleviate the traffic loads in the area until the interchange reopened. A temporary detour was finally created until repairs could be made (Levings and Murray 2019).

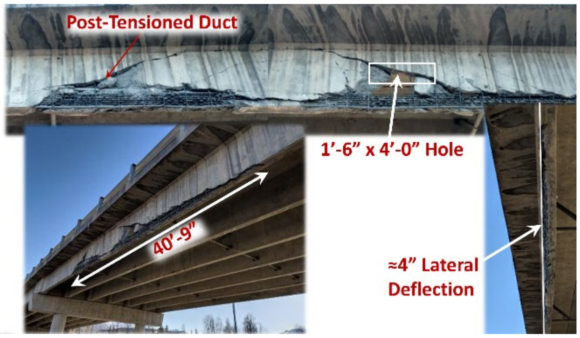


Figure C-40. Collison Damage to Eagle River Overpass (Levings & Murray 2019)

Figure C-41. Established Detour Route (Levings & Murray 2019)

1.1.2. Event Response

The interchange was immediately closed following the collision. Two days after the impact, a detour was created around the region to help alleviate the gridlock until the route could be reopened, as shown in Figure C-41. However, the detour still led to significant backups, at the Glenn Highway is the main travel route into Anchorage (Levings and Murray 2019).

C.11.2 Emergency Planning

No emergency planning information was available.

C.11.3 Assessment

Crews used visual inspections and unmanned aerial vehicles to assess the bridge. Immediately following the collision, photos were collected to identify the damaged portions of the impacted girder. From the visual assessment, it was determined the interchange was unable to be reopened until repairs could be made. Because of this, substantial traffic control was deployed. In total, 31 stirrups were exposed, the girder had a 4-inch lateral deflection, and there was a 1.5ft by 4ft h ole around the post tensioned duct. Two exposed stirrups were also sheared (Levings and Murray 2019).

C.11.4 Rapid Restoration

C.11.4.1 Contracting

To lead the project, the Alaska DOT&PF sent a structural engineer to Anchorage, and selected an emergency project engineer, who lived near the site and had previous experience with a similar bridge impact. The same day of the collision, the on-site structural engineer determined the severely damaged girder needed to be removed. This conclusion was made 10 hours after the collision occurred. The next morning, Alaska DOT&PF selected a contractor for the repairs, and was tasked with providing equipment, a materials list, and personnel for the project (Levings and Murray 2019).

C.11.4.2 Design

The on-site structural engineer helped develop on the spot solutions for the repair. They were responsible for completing field calculations to determine the girder capacity, available equipment loads, and verify the bridge's remaining capacity using pick loads. Additionally, they helped develop the girder removal plan (Levings and Murray 2019).

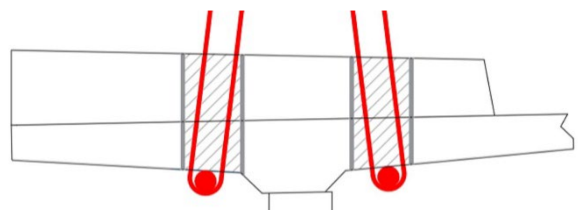


Figure C-42. Girder Removal Cut Plan 71102 (Levings & Murray 2019)

C.11.4.3 Temporary Structure

As part of the temporary repair, the damaged girder was removed four days after the collision. This permitted the interstate to reopen the following day, five days after the collision. Until the final repairs could be made (two years later), the interchange had a lane restriction.

On day 3, the bridge was shored using wooded-like pallets called cribbing (Figure C-43). Because the girder was so heavily damaged, a multi-step process was undertaken to safely remove the girder to avoid buckling. With the cribbing in place on each side of the damaged area, holes were cored through the deck and girder top flange to crack a lifting location for the cranes (Figure C-42). The cranes then lifted the girder up just enough to carry the dead load. Then, the glider was cut longitudinally

Figure C-43. Temporary Shoring Required for Girder Removal (Levings & Murray 2018)

to disconnect it from the adjacent girder. To completely sever the girder into two halves, the damaged area was picked at with an excavator, and then the two halves of the girder were lifted away separately (Figure C-45). This process took place over a few days, and by day 5, the girder removal was complete, and the region was cleaned up (Figure C-44). By 10pm on day 5, the bridge was able to be reopened to traffic until permanent repairs were built in 2020 (Levings and Murray 2019).

Figure C-45. Girder Removal 71104 (Levings & Murray 2019)

Figure C-44. Temporary Repair Clean Up 71106 (Levings & Murray 2019)

C.11.4.4 Permanent Structure

In 2020, the bridge was rebuilt with new rails, sidewalk, and improvements to the diaphragm. It also included the replacement of two exterior girders, the one removed in 2019, and the exterior girder on the opposite side of the bridge, which was also damaged from a previous collision, though that damage was not deemed extreme enough for complete removal (Figure C-46) (Levings and Murray 2019).

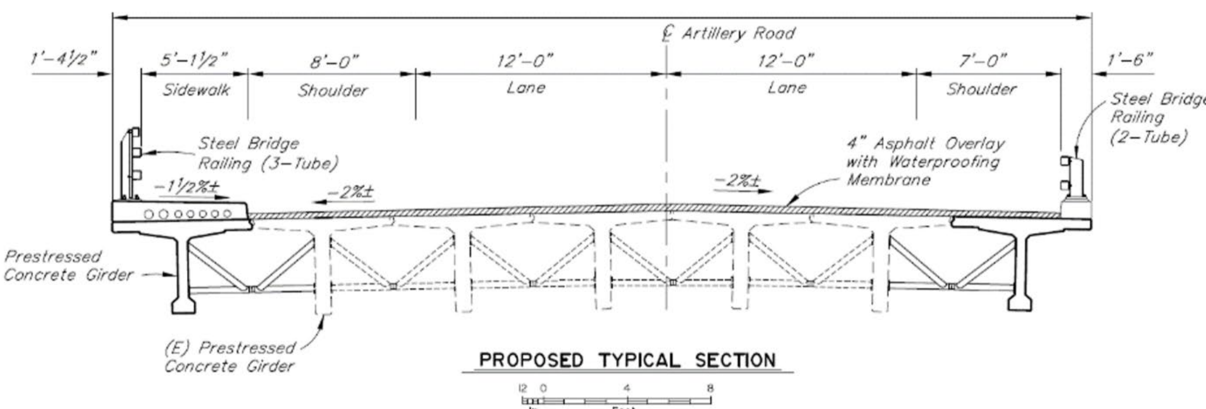


Figure C-46. Permanent Repair Design (Levings & Murray 2019)

C.11.5 Challenges

The strike occurred during winter, which made repairs and work extremely difficult due to the frigid working environment. Furthermore, the lack of possible detour routes put an added stress on the entire situation, as the section of road had an ADT of 60,000 vehicles a day, making it one of the business roadways in all of Alaska (Levings and Murray 2019).

C.11.6 Innovations and Lessons Learned

C.11.6.1 On-Site Structural Engineer for Calculations Expedited Process

The availability of a structural engineer onsite expedited the entire process. They were able to make instant decisions such as the girder removal plan, capacity calculations, and logistical management that would not be possible without someone present (Levings and Murray 2019).

C.11.6.2 Temporary Removal until Permanent Repairs

The decision to remove the girder without the immediate replacement allowed for a quicker reopening than if the girder were restored directly following the strike. The overpass was still able to function with one less girder, even though the lane capacity had to be reduced. Furthermore, the Glenn Highway was able to reopen sooner, alleviating the major traffic disruption (Levings and Murray 2019).

C.12 Interstate 555 Highway 1B Overpass 2017 [Collision]

Table C-12. Interstate 555 Highway 1B Overpass

Case Study Name/Date	Interstate 555 Highway 1B Overpass (2017)
Location	Arkansas, USA
Event Type	Collision
Bridge Name	Highway 1B Overpass
Scope/Costs	Repairs to columns and deck, total approximately $484,000
Planning Techniques/Tools	N/A
Event Response	Immediate closure of both roadways, erection of temporary structure, with later permanent repairs
Assessment Techniques/Tools	Visual Assessment
Rapid Restoration Type	Temporary supports while replacement of damaged columns took place
Innovations	• Temporary Supports • In-House transportation repair work

C.12.1 Introduction

This Case Study was developed based on the information provided by Arkansas Department of Transportation (ARDOT) in the Questionnaire. The information was supplemented by media sources by KARK News 2017 and Arkansas Online 2017.

On June 27th, 2017, a commercial vehicle collided with the Highway 1B overpass over Interstate 555 in Jonesboro, Arkansas, leaving extensive damage to the structure (Figure C-47, Figure C-48, and Figure C-49). Both the interstate and highway were closed because of the collision. Damage included heavily damaged bridge columns, bent cap, and cracking of the deck. A temporary bent was installed to reopen the interstate, and permanent repairs were completed two weeks after the collision, reopening Highway 1B. The entire repair portion of the project along with traffic control cost approximately $247,000. The bridge painting was let to contract for $237,704. All repair work was completed by the Arkansas Department of Transportation (ARDOT).

Figure C-47. Commercial Vehicle Collision with Intermediate Bent (Arkansas Online 2017)

Figure C-48. Damage to Bent (Courtesy of Heavy Bridge Maintenance, ARDOT)

C.12.1.1 Event Response

Both Interstate 555 and Highway 1B were immediately closed following the collision. Once the temporary structure was erected, Interstate 555 was reopened However, Highway 1B was only partially reopen on the undamaged south side to two-way traffic.

It was not until permanent repairs were completed that full traffic was permitted on Highway 1B (KARK 2017).

C.12.2 Emergency Planning

No emergency planning information was available.

C.12.3 Assessment

A visual assessment of the structure revealed the heavily damaged bent that took the brunt of the impact. The four columns that made up the bent sustained significant damage, and one was extensively damaged. The damaged bent caused a few of the girders to have no intermediate support, causing the structure to sag. Immediately following the collision, it was unclear if the structure was in jeopardy of collapsing; however, further investigation indicated the overpass was not in danger of collapse (Arkansas Online 2017).

Figure C-49. Damage to Bent (Courtesy of Heavy Bridge Maintenance, ARDOT)

C.12.4 Rapid Restoration

C.12.4.1 Temporary Structure

The closure of both roadways impacted about 43,000 vehicles a day, so a temporary repair was of the utmost importance. To temporarily stabilize the structure, crews from ARDOT's Heavy Bridge Maintenance section (HBM) arrived within hours of the collision. They installed a temporary wooden bent, which allowed for Interstate 555 to open the following day (Figure C-50A & B). The temporary structure consisted of a steel beam cap held up by a timber braced system. Jacks were placed on top of the cap to support the overpass, which allowed workers to remove and replace the damaged bent (KARK 2017).

C.12.4.2 Permanent Structure

The permanent repairs required crews to work mostly around the clock. Highway 1B was fully opened on July 10th, two weeks after the collision. The permanent structure consists of a new intermediate bent (Figure C-50C). The four steel main girders were found to not require replacement or splicing (KARK 2017).

A

B

C

D

Figure C-50. Temporary Structure (Courtesy of Heavy Bridge Maintenance, ARDOT) (A) Assembly of Temporary Bent (B) Beginning Construction Stages of Temporary Bent (C) New Bent Forms (D) Temporary Bent

C.12.5 Challenges

The closure caused a significant traffic backlog, as upwards of 43,000 vehicles use this stretch of highway/interstate daily. To reduce the impact on commuters, the temporary structure was installed (Figure C-50D).

C.12.6 Innovations and Lessons Learned

C.12.6.1 Temporary Structure for Partial Reopening

Even though repairs were completed in two weeks, keeping Interstate 555 closed for that length of time would be too costly to motorists. Using the temporary structure in tandem with construction on permanent repairs permitted the reopening of Interstate 555 sooner and expedited the entire repair process.

C.12.6.2 In-House Completion

Besides painting, all repairs, including the temporary support and column replacement was completed by the Arkansas DOT. In Arkansas, repairs are generally performed by in-house crews. Arkansas's Heavy Bridge Maintenance crews worked in tandem with District 10 Maintenance crews to take care of the repairs themselves. This saved time by omitting bidding and contracting procedures.

C.13 Arkansas River Bridge Collapse 2002 [Collision]

Table C-13. Arkansas River Bridge Collapse

Case Study Name/Date	Collapse of I-40 Arkansas River Bridge (2002)
Location	Arkansas, USA
Event Type	Collision
Bridge Name	I-40 Webbers Fall Bridge
Scope/Costs	580’ bridge section collapsed; total cost $30 million
Planning Techniques/Tools	N/A
Event Response	Detours and detour route improvements
Assessment Techniques/Tools	Non-linear pushover analysis using software
Rapid Restoration Type	Precast components
Innovations	• Use of prestressed precast girders • Heat straightening

C.13.1 Introduction

On May 26th, 2002, a towboat pulling two empty barges collided into the I-40 Webbers Fall Bridge on the Arkansas River after the boat operator suffered a medical episode, which caused him to blackout (Georgia Tech Research Corporation et al. 2012). The collision resulted in the collapse of four bridge spans and the adjacent piers into the Arkansas River depicted in Figure C-51. Rescue diver response teams were deployed following the collapse and the event resulted in a total of fourteen deaths (FHWA 2002). To expedite the reopening of the bridge, bridge engineers chose to replace the spans with prestressed, precast concrete girders and a single steel span to tie into the existing steel structure. The I-40 Webbers Falls Bridge was reopened to traffic just sixty-four days after the collision (Bai and Kim 2007).

Figure C-51. Collapse of I-40 Webbers Bridge (Georgia Tech Research Corporation et al. 2012)

C.13.1.1 Event Response

Immediately following the collision, the Oklahoma Highway Patrol, and the United States Coast Guard (USCG) assisted in the recovery of vehicles and victims of the bridge collapse. Remaining sections of the Webbers Falls Bridge were stabilized to ensure safety during these recovery efforts. The contractor selected for the repairs had some of its construction crew working downriver at a nearby project and was able to quickly move equipment and workers upstream to assist in bridge demolition and restoration (Wimmer 2004).

Without the I-40 Webbers Falls Bridge crossing, daily commuters and truck traffic had an urgent need for traffic detours across the Arkansas River near the collapsed bridge site. Oklahoma DOT officials funneled traffic onto existing alternate routes; however, these highways and arterials were not built to carry such heavy vehicular traffic. As a result, the Oklahoma DOT completed serious maintenance on these detour roadways such as overlays and pavement resurfacing. The Oklahoma DOT also inspected forty-two bridges along the detours and performed maintenance on two of the bridges to sustain the new temporary traffic volume (Bai and Kim 2007). A total of twelve million dollars was spent on roadway surface enhancements and railroad crossing improvements along the detour routes resulting from the Webbers Falls Bridge collapse (FHWA 2002).

C.13.2 Emergency Planning

C.13.2.1 Crowdsourcing and Information Gathering

Local news outlets touched on the general response efforts and traffic detours that took place immediately following the bridge collapse. Because the event took place in 2002, there were no social media outlets reporting on the event. Social media may have been a more efficient way of communicating traffic detour routes immediately following the event to reduce route confusion. This event relied on local news outlets such as Tulsa World News for sharing current information to the public (Tulsa World 2016).

C.13.3 Assessment

A consultant group of forensic engineers and professional engineering divers investigated the damage to the foundation and submerged substructure of the bridge following the collision. The engineers used in-house software to assess the damage following the investigation. A non-linear pushover analysis was used to construct the events leading up to the collision. An in-house specialist created a video demonstrating a live simulation of the collapse using data from the investigation reports (McLaren Engineering Group 2020).

C.13.4 Rapid Restoration

C.13.4.1 Contracting

A week after the collision, a pre-bid meeting was held, and all potential contractors were invited. This meeting took place without a complete set of bridge plans. Seventeen days after the collision, the contract was awarded. Designers had the plans ready sixteen days following the pre-bid meeting and construction went underway (FHWA 2002).

To promote rapid bridge restoration, the Oklahoma DOT called for A+B Bidding and an incentive/disincentive clause (I/D) for demolition ($50k/day), design ($5k/day), and construction ($6k/hour) contracts. As a result, the demolition was completed four days early, and the construction was completed two-hundred and forty-eight hours early (Bai and Kim 2007).

The Oklahoma DOT built relationships with key organizations affected by bridge construction. These relationships were key to the success of rapid bridge restoration and distribution of heavy traffic volumes to nearby routes. Much of the land surrounding the I-40 Webbers Falls Bridge, including alternate traffic routes, belonged to the Cherokee Nation. Coordination took place between the tribal government and Oklahoma DOT to allow for ease of bridge access for construction vehicles and equipment through Cherokee Nation land. Another key contributor, the FHWA, provided emergency relief funds, technical guidance, and contract assistance during the bridge restoration process. Additional contributions to project success included technical advice provided by the USCG, US Army Corps, and Caltrans (FHWA 2002).

C.13.4.2 Design

Instead of sticking to the original steel design of the bridge, the Oklahoma DOT decided to replace the damaged spans with three prestressed, precast concrete girders. The Oklahoma DOT chose this technique to reduce the time needed for bridge repairs (Bai and Kim 2007). Bridge engineers chose to design one steel bridge span to tie the prestressed, precast concrete spans into the existing steel structure. They also reconstructed the damaged piers, as shown in Figure C-52. To monitor the curing of the concrete sections, the contractor used computer chips to measure the temperature of the setting concrete (FHWA 2002).

Figure C-52. Reconstruction of Piers (FHWA 2002)

C.13.4.3 Permanent Structure

Contractors used heat-straightening to repair existing damaged spans that did not collapse into the river. Heat-straightening involves repeatedly applying small amounts of heat to the damaged regions to increase the workability of the material and to enable easier straightening of the steel girders (FHWA 2002).

During the construction process, the Oklahoma DOT Assistant Bridge Engineer was on call 24/7 to help answer questions or issues that arose during construction and kept the project on schedule. Furthermore, the DOT developed a thirteen-person inspection team to oversee the construction. Some of these team members consisted of retired Oklahoma DOT inspectors or employees. Inspectors also supervised the steel manufacturing to ensure proper QAQC. To give some perspective, typically two inspectors are used altogether for a regular project of this magnitude (Bai and Kim 2007).

C.13.5 Challenges

Scheduling and cost estimating are difficult tasks in emergency situations such as the I-40 Webbers Falls Bridge collapse and reconstruction process. At project completion, the final costs associated with bridge reconstruction were double the original cost estimate, but the project was finished ten months sooner than originally predicted. The use of technology such as iPads and laptops can better monitor construction efficiency and progress. Cameras were used to capture, document, inspect, and monitor the restoration process of the I-40 Webbers Bridge following the collapse. Access to current information on bridge restoration can be used to keep cost estimates and scheduling current throughout the bridge restoration process (Bai and Kim 2007). Figure C-53 shows the completed bridge structure.

Figure C-53. Completed Repairs (FHWA 2012)

During the collision, some of the piers were damaged and needed to be replaced. Demolition of the submerged sections of the damaged piers was difficult. Future research should be conducted to determine the most efficient and safest methods for achieving underwater demolition. More advanced underwater demolition techniques, if known, could have reduced the time required to replace the submerged piers and ensure the safety of crews working on the I-40 Webbers Falls Bridge (Bai and Burkett 2006).

C.13.6 Innovations and Lessons Learned

C.13.6.1 Repair Methods Should Consider Economic Consequences

The I-40 Webbers Falls Bridge is a major east-west commerce route. The cost of keeping the bridge closed had extreme economic consequences. Maintenance of the fifty-seven-mile-long eastbound detour and six-mile-long westbound detour was costly and required traffic control devices throughout (Wimmer 2004). Furthermore, traffic crossing the Arkansas River was suspended for a period during the I-40 Webbers Falls Bridge restoration. Motivations such as great economic loss should be considered in emergency situations such as the collapse of the I-40 Webbers Falls Bridge. Clear and immediate communication with truck traffic, and when feasible, convenient detours with traffic control devices and operators should be put in effect to limit disruption to commerce (Georgia Tech Research Corporation et al. 2012).

C.14 Mathews Bridge 2013 [Collision]

Table C-14. Mathews Bridge Collision

Case Study Name/Date	Mathews Bridge Collision (2013)
Location	Florida, USA
Event Type	Collision
Bridge Name	Mathews Bridge
Bridge Type	Steel cantilever through truss; total length: 7,376 ft; main span: 810 ft
Scope/Costs	Severed main tension chord; closing the bridge for 33 days; total cost of $1.07 million
Planning Techniques/Tools	N/A
Event Response	Immediate closure of bridge, collaboration of engineers, designers, inspectors, fabricators, and emergency responders
Assessment Techniques/Tools	Photos, visual inspection, and strain gauges
Rapid Restoration Type	Temporary chord placement, followed by permanent built-up steel member chord
Innovations	• Temporary chord placement with jacks • Laser scanning gusset plate for quicker and more accurate component manufacturing • Pully system to hoist up components from barges below

C.14.1 Introduction

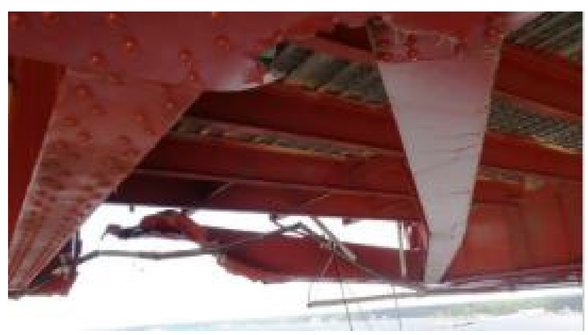


Figure C-54. Severed Tension Chord (Courtesy of Sanya Watts, Watts 2013)

On September 26th, 2013, a US Naval Ship collided with the Mathews Bridge, striking the north bottom truss chord about halfway along the middle span. The stern of the ship was already underneath the superstructure, but the stern ramp was not lowered, and it struck the bridge. The ship's momentum was too great to stop before the damage could ensue. Subsequent inspections found the impact left the tension chord (the bottom member of the truss) cut, which forced a load redistribution, and the floor system took on the "extra" load, as shown in Figure C-54. This put extra stress on members that were not originally designed to resist. Any additional loads from traffic would have put the bridge at risk for collapse. The severed truss element was fracture critical due to its classification as a tensile carrying, nonredundant member. The bridge reopened to traffic thirty-three days after the impact, saving road users an estimated $7 million due to its rapid completion (Watts 2013).

C.14.1.1 Event Response

The bridge was closed immediately after the collision, and all river traffic was suspended. While the shutdown was taking place, the Florida DOT inspected the bridge and found the damage to be severe

(Alipour 2016). The Jacksonville Sheriff's Office coordinated the bridge closure, and the US Coast Guard (USCG) tackled the river shutdown. The USCG also protected the equipment during the repair as needed.

Inspection crews arrived on scene within four hours of the impact (Watts 2013). They sent a Declaration of Emergency letter to the Florida Secretary of Transportation. This decision allowed the Florida DOT to proceed with repairs without abiding by traditional advertising protocols for contracting (Alipour 2016).

To determine the best course of action, the Florida DOT created an emergency response team, which consisted of bridge engineers, surveyors, contractors, fabricators, and inspectors. Together, the team generated a bid package within seventy-six hours of the collision, working through the nights to complete the package at record speed. An incentive/disincentive clause for $50,000 per day was included, and the schedule set for forty days (Alipour 2016).

Ongoing construction projects in the surrounding areas were suspended to provide alternative routes for commuters and travelers. In some cases, crews from these job sites were reassigned to work on the Mathews Bridge repair.

C.14.2 Emergency Planning

C.14.2.1 Crowdsourcing and Information Gathering

The accident occurred around 2pm on September 26th, 2013. Witnesses captured a cell phone video that was later used during the analysis.

To keep the public in the loop, daily announcements were made through the Florida Public Information Office and distributed to citizens through various forms of media. The Florida DOT wanted to not only repair the bridge as quickly as possible, but also to teach the general public the reasoning behind the repair methods. The Florida DOT addressed concerns from the public and emphasized the importance of safety. To notify motorists about the closure, an Intelligent Transportation System (ITS) was used to provide information on alternative routes and detours. Posts on social media highlighted key progress, and on-site press conferences were held regularly (Watts 2013).

C.14.3 Assessment

After the collision, initial inspections during the evening consisted of taking photographs and documenting the damages to determine global stability and the best design options.

The next day, climbing inspectors arrived on scene to scour the bridge for more detailed views at areas of concern. Using photos collected from the scene and computer software, Florida DOT bridge designers worked together to brainstorm the best way to repair the bridge. Meanwhile, a team was organized to generate corresponding CAD files, and another to develop the contracts (Watts 2013).

The structural integrity of the bridge was originally unknown. It was concluded that the severed chord needed to be pulled back together to reconnect the load path, which would also remove the additional stresses on other elements.

Figure C-55. Strain Gauge Installation and Wire Management (Courtesy of Sanya Watts, Watts 2013)

To monitor the effects of load redistribution during the repair, bondable foil strain gauges were installed on the damaged north truss to monitor the initial and redistribution loads on the bridge once construction began, as shown in Figure C-55 (Alipour 2016 and Watts 2013). This was especially important during the jacking and de-tensioning processes of the chord. The gauges were also used to monitor for buckling in the upper chord during repair, and on the south truss to have a preliminary basis to compare the data from the north truss (Alipour 2016).

C.14.4 Rapid Restoration

C.14.4.1 Contracting

The bid was awarded two days after the pre-bid meeting, and the pre-construction meeting was held a few hours later. Crews worked 24/7 to complete the project (Watts 2013).

C.14.4.2 Temporary Structure

A temporary repair was put in place to permit construction of the damaged cross members, then a final chord replacement was designed, and traffic was returned (Alipour 2016). Surveying was completed each day to monitor the deck and floor beams for any signs of creep (Alipour 2016). At each completion of the repair work (temporary and final), load tests were conducted using Florida DOT flatbed trucks driven across the deck. The trucks stopped at three locations and the bridge was monitored for performance, as shown in Figure C-56 (Alipour 2016).

Figure C-56. Load Testing (Courtesy of Sanya Watts, Watts 2013)

C.14.4.3 Permanent Structure

The first step in the repair process was to install the scaffolding that would be used by workers, as shown in Figure C-57. This was challenging due to load constraints on the bridge, so the entire bridge repair was completed in stages. Once the scaffolding was in place, a pair of beams were positioned so they could be anchored to the eastern span to provide some geometric restoration to the north truss, acting like a strong back and saddle system. A plant in Tampa, FL manufactured seventy-foot long beams and then trucked the beams to the bridge site. Because of the length of the beams in transportation, special permits had to be attained, and a cable pully system was used to set them into place.

Figure C-57. Scaffolding on Mathews Bridge (Courtesy of Sanya Watts, Watts 2013)

With support from the strongbacks, the damaged cord was cut and removed. The three-foot chunks were lifted to the deck and saved for further inspection, as shown in Figure C-58. From here, the temporary lower chord could be installed, which consisted of four sixty-six-foot threaded rods. Fortress anchors were bolted to the lower chord with one hundred high strength bolts. Once

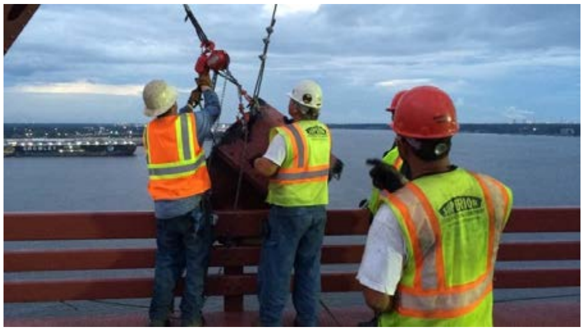


Figure C-58. Hoisting up Damaged Chord Components (Courtesy of Sanya Watts, Watts 2013)

in place, jacks were used to tension the temporary chord. This was completed incrementally over the course of five days. Initially, the gap in the chord was not closing, and this was later found to be caused by relaxing of the bars. A "jack then relax" system was used to gradually to close the gap (Watts 2013).

With the temporary chord in place, other repairs could then take place on the damaged components, as shown in Figure C-59. The north bracing failed due to block shear at a gusset plate and buckling occurred in many members. The floor beams that were misaligned did straighten back out with the realigned geometry of the temporary chord, but the damaged gusset plates were not realigned and stiffened with angles (Watts 2013).

Figure C-59. Damaged Gusset Plate (Courtesy of Sanya Watts, Watts 2013)

To prepare for the permanent chord member, the adjacent gusset plates needed to be heat-straightened. Heat was only applied one minute at a time with a torch, and then the plates were slowly bent back into shape. This took about one hundred man-hours to complete. From here, a stub beam was installed to allow for easier installation of the permanent chord by splicing the new member to this stub beam instead of the panel point (Watts 2013).

On day twenty-two of the repair, the crew began splicing the new chord into place. The new chord was a built-up section that was dismantled once it reached the site and then reassembled in place and bolted into its final position. The beam weighed eight kips, making it too heavy to be lifted into place, and too dangerous to hoist forty feet off the side of the bridge while weaving through the truss. A "double-bolt and cheese filler plate method" was used to strengthen the gusset plate damaged during the impact. This could be done without unzipping the rivets of the entire connection as the "cheese" plate was cut to fit around the bolts (Watts 2013).

After the new chord was set in place, the temporary chord was de-tensioned, and the scaffolding removed. The project was then complete (Watts 2013).

C.14.5 Challenges

Monitoring the force paths and redistribution is instrumental during the repair and evaluating the integrity/safety of the repaired bridge. To streamline the strain gauge installation process, the locations were pre-mapped out. These regions were then cleaned and prepped for placement, including surface finishing and waterproofing. The gauges themselves were delicate and welded in-place. Over thirteen miles of wire was run across the bridge, linking all the gauges to a central data acquisition system (DAQ). Information in the DAQ could be accessed from anywhere, allowing for real-time monitoring from any location, as shown in Figure C-60. Delicate coordination had to take place not to damage the gauges or their wires throughout the repairs.

Figure C-60. Data Monitoring (Courtesy of Sanya Watts, Watts 2013)

A major challenge for the project was the weight restriction on the bridge due to the redistribution of the load from the severed chord member. Cranes and other heavy equipment could not be brought on the bridge, so crews had to assemble some items in place (like the permanent chord) or use a pully system, as shown in Figure C-61.

For the “double-bolt and cheese filler plate” a challenge arose with meeting the precision needed to cut the “cheese plate” bolt holes. The solution came from using the surveying equipment already on site. A laser scanner was used to map out the existing gusset plate with an accuracy of 0.5mm. The maintenance crews even bult a bracket to hold the laser scanner off the side of the bridge to get the best angle for the scan. The results were then imported into CAD for the fabricator to manufacture.

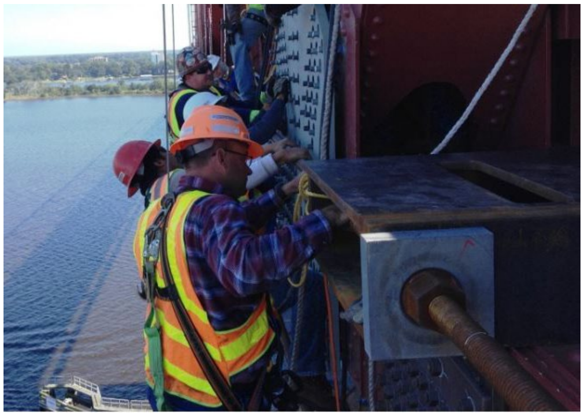


Figure C-61. Repairs made next to Temporary Chord (Courtesy of Sanya Watts, Watts 2013)

C.14.6 Innovations and Lessons Learned

C.14.6.1 Laser Scanning for Accurate and Precise Measurements

To pull off such a monumental task, quick and efficient coordination between inspectors, designers, contractors, and fabricators had to take place. Solutions such as using the laser scanner to develop CAD files for the “cheese plate” or the perfect fit of the built-up new chord while assembled in place would not have been feasible if there was not clear communication.

C.14.6.2 Declaration Letter

The Declaration of Emergency sent to the Florida Secretary of Transportation paved the way for easier project contracting and sped up the entire repair process.

C.14.6.3 Weight Restriction Pully System

The reduction of load capacity on the bridge during repairs had a major impact. The decision to use a pully system to hoist up components from the river below was a creative solution to avoid the use of heavy cranes or machines on the bridge deck.

C.14.6.4 Structural Monitoring

Maintaining consistent structural monitoring during the assessment and repair of the structure ensure worker safety, but also verify the repairs were working.

C.15 San Jacinto River I-10 2019 [Collision]

Table C-15. San Jacinto River I-10 Bridge

Case Study Name/Date	San Jacinto River I-10 Bridge (2019)
Location	Texas, USA
Event Type	Collision
Bridge Name	I-10 San Jacinto River Bridge
Scope/Costs	Severe damage to several columns, total cost $3 million
Planning Techniques/Tools	N/A
Event Response	Multi-jurisdictional Unified Command, detour routes
Assessment Techniques/Tools	Underwater sonar images showing underwater damage, Diver observation, Expert on-site assessment, Videos
Rapid Restoration Type	Dolphin structures, Fender System
Innovations	• Drone-Based Data Collection • Bridge collision avoidance measures

C.15.1 Introduction

Due to the remnants of Tropical Storm Imelda, which cause the strong current in San Jacinto River, nine barges had broken away from their moorings at the San Jacinto River Fleet on September 20th, 2019. Two of them hit the I-10 Bridge, causing extensive damage to the bridge's concrete columns, as shown in Figure C-62. The I-10 Bridge was immediately closed, and crews implemented a lengthy detour route. After the barges were removed, TxDOT reconfigured eastbound and westbound traffic, with two lanes in each direction, on the eastbound side of the bridge until permanent repairs could be made (Begley 2019; The Maritime Executive 2019).

Figure C-62. Severe Column Damage from Barge Impact (Clement 2019)

C.15.1.1 Event Response

Immediately following the collision, a Unified Command was established. This command was made up of the U.S. Coast Guard, the Texas DOT, the Barge Company, and the Texas General Land Office (Coast Guard News 2019)

Additionally, detours were establised. To help reduce congestion and the inconvenience to drivers, the Texas Department of Transportation (TxDOT) waived the tolls on the Sam Houston Tollway Bridge, which was located along the main detour (Delony & Carter 2019). The recommended route extended motorists' commute by 20 miles each way until the westbound lanes were cleared as safe for traffic loads. Then, they were reconfigured to two 11' wide lanes in each direction until repairs were finalized (Begley 2019).

C.15.2 Emergency Planning

C.15.2.1 Crowdsourcing and Information Gathering

The U.S. Coast Guard Sector Houston-Galveston received a report at about 12:05 am. that several barges had floating away from their mooring. The Coast Guard dispatched a helicopter and response boat, who confirmed that two barges had struck the I-10 bridge, causing visible column damage. Around 4am, TxDOT closed all lanes of the I-10 Bridge. After the initial reports, drone footage was captured and released as part of the investigation (Clement 2019).

C.15.3 Assessment

The drone footage was first used to assess the initial damage. Limited access and high flood waters made contact difficult, so the footage was vital for initial inspections (Clement 2019).

The Monday following the event, professional divers and state engineer teams inspected the bridge, confirming damage to several support columns on the westbound span of the double bridge. Initial speculation from TxDOT included large sections of damage, requiring the need of a full column replacement (Begley 2019).

These assessments also confirmed that the eastbound bridge was unaffected by the barge hits. Thus, TxDOT felt confident enough to reopen the eastbound lanes to traffic.

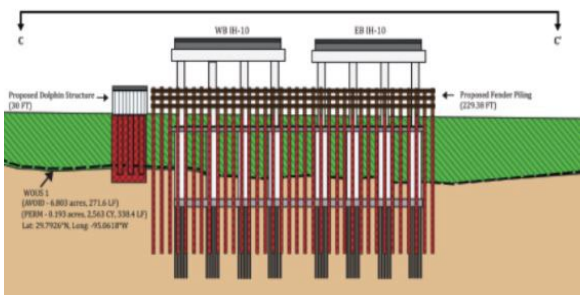


Figure C-63. Dolphin and Fender Repair (Courtesy of Highlands Star Crosby Courier Newspaper, Star Courier News 2020)

C.15.4 Rapid Restoration

C.15.4.1 Contracting

A contractor was hired for the project in mid-October, and construction commenced near the end of the month. The contract was estimated at $3 million and was scheduled for completion in February of 2020 (Hernandez 2019). Most of the repairs focused on strengthening and stabilizing the damaged columns.

On January 22, 2020, the Texas Department of Transportation announced all main lanes of the I-10 Freeway at the San Jacinto River were back open (ABC13 2020).

C.15.4.2 Permanent Structure

The final repairs for the I-10 bridge included the replacement of the damaged dolphin structures and fender systems. These were crushed by the barges and are the bridge’s main defense against similar collisions. In total, four dolphin structures were replaced, each capable of withstanding 30 LF. The corresponding fenders were built with 18-inch diameter steel that was coated with marine-grade epoxy. The fender system consisted of 77 steel pilings in total, and several were covered in riprap, as shown in Figure C-63 (Starcouriernews 2020)

C.15.5 Challenges

The closure of the I-10 bridges significantly impacted travel times in the area. TxDOT had to carefully plan a detour route that would handle the increase in traffic loads. The waiver of tolls on the Sam Houston Bridge helped reduce the frustration felt by motorists.

Figure C-64. Barge Removal (McCormack 2019)

Furthermore, there were many concerns centering around the removal of the barges (Figure C-64). The two barges were carrying toxic substances, and there was worry they had already, or could cause, contamination into the San Jacinto River. Moreover, during repairs, barge traffic was limited to prevent further damage. The I-10 bridge had been struck multiple times before by barrages, so it was not an uncommon event (McCormack 2019). Additionally, the San Jacinto Waste Pits Superfund Site is located adjacent to the bridge, so there was concern removing the barges might impact the site. Fortunately, the US Coast Guard confirmed there was no adverse impact to the river, or the Superfund Site caused by the barge collision (Begley 2019).

C.15.6 Innovations and Lessons Learned

C.15.6.1 Special Considerations Needed for Problematic Areas

The bridge had experience frequent collisions with barges. In February of 2019, the bridge was struck by a barge in the exact same location. The damage caused by this collision took about 3 months to repair (Delony & Carter 2019). Dolphins, fenders, and other types of protective barriers should be installed and regularly maintained near bridges that experience frequency collisions. This reduces the likelihood of damage to the structure, and prevents major economic disruption caused by full bridge closures or even partial openings.

C.15.6.2 Drone-Based Data Collection

In this instance, the damage to the columns could not be investigated without a snooper vehicle. However, due to the unknown extent of the damage, it was too dangerous for crews to load up the bridge with heavy vehicles. Using Drones or other unmanned aerial systems (UAS) are a great alternative to inspection difficult to reach or unsafe regions of structure. The fast-moving flood waters also made the structure inaccessible by boat immediately following the collision, so the captured drone footage provide the opportunity for inspectors and engineers to be able to assess the situation without putting any personnel in harm's way. Drone-based data collection provides a rapid means to comprehend damage and plan for a repair solution.

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C.16 Scottsburg Bridge 2017 [Collision]

Table C-16. Scottsburg Bridge

Case Study Name/Date	Scottsburg Bridge (2017)
Location	Oregon, USA
Event Type	Collision
Bridge Name	Scottsburg Bridge
Scope/Costs	$300,000, full bridge closure
Planning Techniques/Tools	Flash alerts from 911 calls to DOT
Event Response	Full bridge closure, 100-mile detour route
Assessment Techniques/Tools	Visual assessment, laser scans, and MDT testing
Rapid Restoration Type	Heat straightening and member strengthening
Innovations	• Using Lidar to look for minute deflection in members • Using scan data to generate finite element model for load rating analysis

C.16.1 Introduction

On Wednesday, April 12th, 2017, a semi-truck crashed into one of the compression members on the historic Scottsburg Bridge along Highway 38 near Scottsburg, Oregon, as shown in Figure C-65. The through-truss was originally constructed in 1929 and had been a repeat victim of collisions. The narrow, windy road leading up to the bridge caused it to be frequently hit. This time, however, the damage was significant, and the bridge was fully closed for 4 days, forcing drivers to use a 100+ mile detour. Local school districts also were forced to use the detour, adding 1.5+ hours to student's bus rides to and from school (KPIC 2017b). The Oregon DOT hired a contractor to perform heat straightening on the damaged member and called in its geometronics group to take laser scans of the bridge to identify any other areas of hidden damage (Kinney 2017).

Figure C-65. Truck on Truss Member (Oregon DOT 2017)

C.16.1.1 Event Response

Calls about the collision were first reported to dispatchers. Oregon DOT maintenance crews were dispatched shortly after. The bridge was immediately closed following the collision and stayed closed for 4 days.

C.16.2 Emergency Planning

The Scottsburg Bridge had been hit multiple times since its original construction in 1929, as shown in Figure C-66. The combination of the approach roadway and narrow structure routinely left a pile of side mirrors, awnings, and other car parts in the Umpqua river below. ODOT has placed several "narrow bridge" signs before each final approach to the bridge to warn drivers. On the opposite side of the main collision, they even wrapped a timber beam to the compression member to protect it from future crashes. Unfortunately, during this collision, that was not the crash location.

Figure C-66. Original Construction (Oregon DOT 1929)

C.16.2.1 Crowdsourcing and Information Gathering

The Oregon DOT uses a Flash Alert system that automatically notifies the DOT when there is a collision, or a 911 call related to a bridge. This was how they were notified in the case of this collision. The district maintenance staff receive the alert from the system and are the first on scene from the DOT to investigate. Then, if their initial assessments warrant further exploration, they can call in for engineers to come out and perform their assessment. This is the process that occurred for the Scottsburg bridge. Figure C-67 shows some of the damage after the truck was removed from the truss.

Figure C-67. Side View of Member Distortion (Dobson 2017)

C.16.3 Assessment

After the wreck was removed from the bridge, the focus of the inspection was the damaged compression member. A visual inspection indicated this steel truss element was severely deformed, including a change in section thickness, deflection, paint delamination, local flange buckling, and high stress points, as shown in Figure C-68. Measurements were taken of the deformed section, and paint was removed to better view the metal. MT testing was performed on several areas to show crack propagation, which was near the web and flange interface. Cracks near some of the member's rivets and in an angle piece of the nearby floor beam were also noted (Dobson 2017).

Figure C-68. Compression Member Buckling (Dobson 2017)

Prior to the 2017 crash, the bridge was part of an Oregon DOT 3D mobile scanning project, which gathered 3D point cloud data. After the crash, there were still signs of distress after the visual inspection and MT testing. Oregon DOT's geometronics unit was called to scan the bridge again to help spot the regions of damage. The data collected was compared to the previous scans which indicated one of the truss lines had deflected down by approximately 2in. The bridge's truss features a continuous span over all the intermediate bents, which caused concern with the 2in deflection. This meant the structure's load path had been disrupted and redistributed to members not designed to carry that load. A load rating was then performed on the structure and found that the previous rating needed to be updated, as the interior bents were now carrying significantly more load in some cases (Kinney 2017).

C.16.4 Rapid Restoration

C.16.4.1 Contracting

The Oregon DOT hired two contractors for the bridge using emergency contracts. The first contractor was responsible for the temporary repairs and the second was for the permanent solution.

C.16.4.2 Temporary Structure

Heat straightening was performed on the damaged member. The crews had to complete multiple cycles for the steel truss to shift back into place. However, since the bridge had been hit in this location before, and had undergone heat strengthening, it was determined that a more permanent repair needed to take place for increased strength.

C.16.4.3 Permanent Structure

For the permanent strengthening repair, additional plates were added to the damaged element to reinforce the member. This repair was completed 9 days after the collision, and the bridge was able to fully reopen after this success.

C.16.5 Challenges

Even after the visual assessment was complete, the engineers and inspectors on site were puzzled, as water was pooling on the deck near where the damaged member was located, even after the heat straightening. This indicated there were additional deflections caused by the accident, but crews could not determine where. At this point, the geometronics group was called on scene to perform the scans and help identify the areas of further damage (Figure C-69) (Kinney 2017).

The 100+ mile detour put an added pressure on the project. Moreover, dozens of local children were unable to get to school, and busses had to add an extra 1.5 hours to their routes each day because of the detour. Crews worked upwards of 18 hours a day to complete the heat strengthening repair over the weekend following the collision. Furthermore, the local school districts also worked out contingency plans with the Oregon DOT for alternative routes for the kids to get to school should the repair take longer than the weekend. Luckily, one lane of traffic was able to open the following Sunday (KPIC 2017a).

Figure C-69. Floorbeam Buckling (Dobson 2017)

C.16.6 Innovations and Lessons Learned

C.16.6.1 Lidar Scans

Having pre-collision lidar scan data of the bridge prior to the collision proved to be an asset. This provided the baseline conditions that future scans could be compared to, and helped locate additional areas of damage that were undetectable with visual inspections alone. This data also made it easier to perform the load rating analysis, as the change in load path could easily be identified and current conditions of truss elements could be modeled with higher accuracy.

C.17 Skagit River Bridge 2013 [Collision]

Table C-17. Skagit River

Case Study Name/Date	Collapse of I-5 Skagit River Bridge (2013)
Location	Washington, USA
Event Type	Collision
Bridge Name	Skagit River Bridge
Scope/Costs	All six lanes of a single span (Northbound and Southbound) of Interstate 5 collapsed, total cost about $18 million
Planning Techniques/Tools	911 calls to gather information
Event Response	Multi-jurisdictional, detour routes, and freight alerts to inform truck traffic
Assessment Techniques/Tools	Photos, eyewitnesses, measurements, collapse video, and CAD drawings
Rapid Restoration Type	Temporary modular bridge; lateral bridge slide – ABC technique
Innovations	• Modular truss bridge as a temporary structure to reopen interstate quickly while construction took place alongside • Reusing undamaged components customizing new span characteristics to match the existing bridge.

C.17.1 Introduction

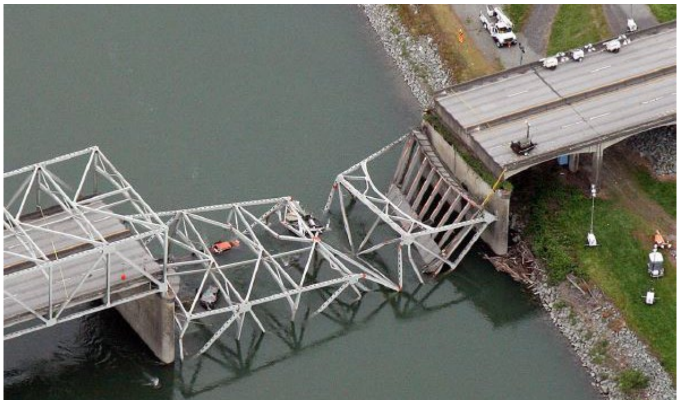

Figure C-70. Collapse of Skagit River Bridge (Washington State DOT 2014)

On May 23rd, 2013, an overheight truck crashed into the top portal on Span 8 of the Skagit River Bridge on Interstate 5, near Mt. Vernon, Washington. This collision caused the span to collapse, falling into the Skagit River, along with several cars on the bridge, as shown in Figure C-70. (National Transportation Safety Board 2014). No one was seriously hurt, but the bridge did leave Interstate 5 closed for 27 days until crews could install a temporary structure. Using Accelerated Bridge Construction (ABC), a new span was built parallel to the temporary bridge. When it was nearly assembled, the new span was slid into place and final assembly was completed, only four months after the incident. Crews also raised the elevation of the arched portals on the rest of the bridge to a height of 18 feet to prevent future collisions. This was accomplished by partially dismantling the portals and reassembling them in a different arrangement (Washington State DOT 2014). The temporary structure and subsequent replacement cost $18 million, and all but $1 million was funded by the USDOT (Associated Press 2013). Overall, this project serves as an excellent example of rapid restoration, stemming from the emergency response and installation of a temporary structure to completing the new spans and restoring the entire bridge.

C.17.1.1 Event Response

Traffic engineers had to re-route I-5 traffic through the cities of Mt. Vernon and Burlington to divert interstate traffic around the collapsed bridge. About 71,000 vehicles were impacted daily during this time. Alerts were cast out to truck traffic via Freight Alerts.

C.17.2 Emergency Planning

As soon as the collapse occurred, there was an immediate response from land, air, and water. The Skagit County Sheriff's Office, Mt. Vernon/Burlington Police and Fire, and the Washington Department of Transportation (WSDOT) quickly responded on the ground. The nearby Whidbey Island Air Station (Navy) sent air support, and the US Coast guard sent in rescuers from the river (Alipour 2016).

C.17.2.1 Information Gathering

Shortly after the collision and subsequent collapse, the Skagit County Emergency Communications Center received 911 calls. Operators were told the bridge had collapsed. This information was verified by the responders first on scene, about 3 minutes after the first 911 calls (National Transportation Safety Board 2014).

C.17.3 Assessment

The National Transportation Safety Board (NTSB) interviewed several drivers who either passed the overheight vehicle or who were on the bridge at the same time. These citizens provided eye-witness testimony and identified where the strike occurred. The security camera of a nearby car dealership captured the collapse on video, and this video was used to identify the cause of the collapse. Photos and component measurements were also used to determine the failure mechanism (National Transportation Safety Board 2014).

C.17.4 Rapid Restoration

C.17.4.1 Contracting

Prior to the collision, WSDOT had an emergency contract with a local construction firm to complete repairs on an ad hoc basis. To get the project implemented rapidly, an A+B Bidding Process was implemented, and included the use of incentives for early milestone completions. They also left the exact type of bridge (prestressed vs. steel) up to the winning firm. This encouraged faster construction while still making sure the project was completed at a reasonable price (Washington State DOT 2016).

Figure C-71. Temporary modular bridge (Washington State DOT 2014)

C.17.4.2 Temporary Structure

The temporary structure used was a side-by-side dual lane modular truss ACROW bridge. This structure had to maintain the same river height clearance as before (or could be higher) and ensure the installation was quick to reduce traffic disruption, and not increase seismic loads on the structure in case of an earthquake (Washington State DOT 2014). This system is shown in Figure C-71. The temporary structure was assembeld and installed by the emergency contractor already establisehd by WSDOT prior to the collision.

Figure C-72. Prestressed Girders Lifting into Place (Washington State DOT 2014)

C.17.4.3 Permanent Structure

The replacement span was constructed out of prestressed girders with extra wide flanges and high-strength concrete closure pours, as shown in Figure C-72. This design was chosen to minimize the amount of curing time for the deck once all the girders were set into place. The girders used light-weight concrete to match the weight of the old truss – this allowed the original bents to be used, saving time and money (Washington State DOT 2016). Other designs considered for the replacement included a steel through-truss (to match the remaining spans), which was deemed too time-intensive, or steel plate girders with a concrete deck. Ultimately, the winning firm chose the prestressed concrete design.

The replacement span was constructed alongside the bridge, and then slid into its final position; this kept traffic flowing during the construction and only required a full closure for one day to place the permanent span (Washington State DOT 2013). The slide used vertical and horiztontal jacking system along with a rail system on top of tempoary bents to shift the structure. (Washington State DOT 2014).

C.17.5 Challenges

The decision to use lightweight concrete for the girders created some challenges, as it was difficult to maintain the correct aggregate weight and moisture contents, so extra attention was paid to the mix design in these instances. Also, the closure pour design had not yet been thoroughly tested for durability, as this is a relatively new construction method, and laboratory tests have not yet been conducted to verify its longevity. This design is shown in Figure C-73. WSDOT may find that this technique does not have the longevity promised, but time will determine its viability as a future alternative design (Washington State DOT 2016).

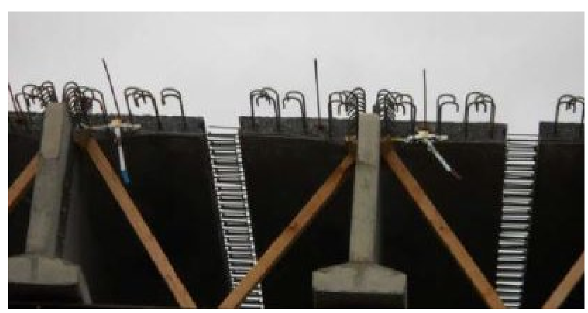

Figure C-73. Closure Pours Connecting the Girders (Washington State DOT 2016)

C.17.6 Innovations and Lessons Learned

C.17.6.1 A+B Bidding

The decision to use A+B Bidding in combination with early milestone completion minimized the construction time and project delays.

C.17.6.2 Temporary Modular Bridge

Erecting a temporary modular bridge, as shown in Figure C-74, reduced the need for traffic detours around the collapsed structure. The nearby bridges in the towns of Burlington and Mt. Vernon did not have adequate capacities to carry interstate traffic levels, so the temporary structure also reduced the impact on these communities and ensured commerce could proceed as normal.

Figure C-74. Traffic Flow with Temporary Structures (Washington State DOT 2016)

C.17.6.3 Prefabricated Bridge Elements and Systems (PEBS)

Using PEBS in tandem with constructing the bridge adjacent to the temporary structure minimized traffic disruption and reduced the overall length of construction time.

C.18 Pennsylvania Department of Transportation P3 2012 [Procurement]

Table C-18. Pennslyvania Department of Transportation P3

Case Study Name/Date	Pennsylvania Department of Transportation P3 (2012)
Location	Pennsylvania, USA
Event Type	Procurement
Bridge Name	Did not select one bridge for this Case Study/Numerous
Scope/Costs	Repairs to 558 Bridges
Planning Techniques/Tools	ROW and permitting pre-approvals
Event Response	Formation of a Public-Private Partnership
Assessment Techniques/Tools	Criteria matrix
Rapid Restoration Type	ABC using standardized drawings and prefabricated components
Innovations	• Public-Private Partnership • 28-year build and maintenance contract

C.18.1 Introduction

To address the growing issue of the Commonwealth of Pennsylvania's 4,500+ poorly rated bridges, the Pennsylvania Department of Transportation (PennDOT) formed a Public-Private Partnership (P3) with the Plenary Walsh Keystone Partners (PWKP) group. This initiative replaced 558 bridges throughout Pennsylvania over the course of three years. Once the bridges were built, PWKP will maintain the bridges for the following 25 years, and then at the end of the 28-year contract, will hand the bridges back over to PennDOT. Most of the bridges involved in the project are small rural or medium-sized state-owned bridges, and not large interstate structures. The repairs mostly consisted of Accelerated Bridge Construction (ABC) to meet the three-year deadline. This innovative solution paved the way for similar contracts with other DOTs looking at unique solutions to help repair their aging infrastructure (Plenary Walsh Keystone Partners 2019). A finished bridge through the project is shown in Figure C-75.

Figure C-75. A Bridge Built part of the P3 Project (Plenary Walsh Keystone Partners 2019)

C.18.2 Emergency Planning

C.18.2.1 Crowdsourcing and Information Gathering

Clear communication from the start was used to keep good relations with the public. It was decided that a website would be created to provide regular updates on closures or detour re-routes to help keep traffic flowing and reduce disruption to commerce. Furthermore, the design lives of the bridges were all 100 years; this lifespan was chosen to reduce future traffic impacts. (Plenary Walsh Keystone Partners 2019).

C.18.3 Assessment

To determine which bridges qualified for the project, PennDOT investigated over 2,000 of its poorly rated bridges. Bridge age, type, size, average daily traffic, and environmental impacts were key factors in the decision. The standardized ABC approach paired best with smaller, single, or double span bridges, so this description helped narrow down the selection of the final 558 (Plenary Walsh Keystone Partners 2019).

C.18.4 Rapid Restoration

C.18.4.1 Contracting

The P3 model was made possible by Governor Tom Corbett in 2012, when he signed the PA General Assembly into effect, which aims to rapidly improve Pennsylvania's aging infrastructure, and to save the taxpayers money. It is more inexpensive to group the 500+ bridges into one giant contract, rather than completing individual ones. Furthermore, the cookie-cutter approach may cost more upfront, but significantly reduce spending later in the project (Plenary Walsh Keystone Partners 2019). An example of a completed bridge is shown in Figure C-76.

PWKP group is made up of the following companies:

- HDR, Inc – lead design firm
- Walsh Infrastructure Management – maintenance crew for entire contract
- Walsh/Granite JV – lead contractor
- Plenary Group USA Ltd. + Walsh Investors, LLC – finance groups

Throughout the contract, the Pennsylvania Department of Transportation remained owners of the bridges (Plenary Walsh Keystone Partners 2019).

To encourage more involvement from other companies, outreach opportunities to the disadvantaged business enterprise (DBE) community were organized. These meetings provided information as to how these smaller subcontractors could become involved in the project (Plenary Walsh Keystone Partners 2019).

To finance the consortium, performance-based payments were made periodically throughout the contract. More money was paid upfront during the bulk of the construction, and then tapered as the responsibility shifted toward maintenance (Plenary Walsh Keystone Partners 2019).

Figure C-76. A Bridge Built part of the P3 Project (Plenary Walsh Keystone Partners 2019)

C.18.4.2 Permanent Structure

To speed up the repair process, Right of Way (ROW) and other permits were attained prior to construction. Bridges were screened in batches to expedite the process further (Plenary Walsh Keystone Partners 2019).

To be able to rapidly repair 558 bridges, the group developed standardized designs which used many prefabricated components that were created off-site. These prefabricated units were trucked to the sites and quickly installed using ABC technologies (Plenary Walsh Keystone Partners 2019).

C.18.5 Challenges

One challenge with this project was to prevent the appearance of the formation of a monopoly on Pennsylvania bridge repairs. The consortium gained the "rights" to repair hundreds of bridges, leaving other construction and design firms out of luck. However, the decision to expand the program to include DBE companies opened the door for others to take part, spreading the wealth and preventing the formation of a monopoly.

Additionally, the development of standard plans that would work for multiple bridges was also challenging. By grouping similar bridges together, they consortium as able to determine the number of plan sets required, and to also speed up the work.

C.18.6 Innovations and Lessons Learned

C.18.6.1 Application of P3 Model

Most of the lessons learned with this project were from the procurement and asset selection stages. Acquiring materials can be challenging, especially when mass quantities are required for standard components. Moreover, learning how to manage a multi-company project, such as determining who oversees what, and which company(ies) are responsible for which portions can be challenging. The goal of this project was to not only repair hundreds of poorly rated bridges, but to also learn how to implement the Public-Private Partnership. The P3 model could be expanded to other projects or states, so PennDOT really focused on learning the logistical side of the project and understanding what worked and what did not (PennDOT P3 Partnerships 2019). Figure C-77 shows an example of a bridge finished through the project.

Figure C-77. A Bridge Built part of the P3 Project (Plenary Walsh Keystone Partners 2019)

C.19 I-35W Mississippi River Bridge Collapse 2007 [Man-made]

Table C-19. I-35W Missippi River Bridge Collapse

Case Study Name/Date	I-35W Mississippi River Bridge Collapse (2007)
Location	Minnesota, USA
Event Type	Man-made
Bridge Name	I-35W Mississippi River Bridge
Scope/Costs	456’ of main span deck truss + surrounding spans collapsed into Mississippi River, impacting all 8 lanes
Planning Techniques/Tools	911 Calls
Event Response	Unified Command System Implemented
Assessment Techniques/Tools	Collapse video, photos, eyewitness testimony
Rapid Restoration Type	Precast segmental bridge construction
Innovations	• Structural health monitoring of the replacement bridge • Connection inspections

C.19.1 Introduction

The original fourteen span I-35W Mississippi River Bridge was opened in 1967 by The Minnesota Department of Transportation (MnDOT), as shown in Figure C-78. The structure carried both northbound and southbound traffic. Unknown at the time, the center deck truss portion was connected by under-designed gusset plates. Furthermore, the bridge had been deemed structurally deficient since 1991 (National Transportation Safety Board 2007).

On August 1st, 2007, the I-35W Bridge collapsed due to a gusset plate failure on the main span, as shown in Figure C-79. 111 vehicles were involved, 13 people died, and 145 were injured. The NTSB ruled the collapse was due to designer error and lack of quality control of the gusset plate, which failed due to increased loading from construction equipment/supplies in combination with previous bridge modifications and an insufficient design capacity. In total, about 1000’ of the bridge collapsed into the Mississippi River.

A replacement bridge was built shortly after the collapse, and remote sensing technology was implemented to monitor the health of the structure and alert official of possible changes to the substructure conditions (Collins et al. 2014).

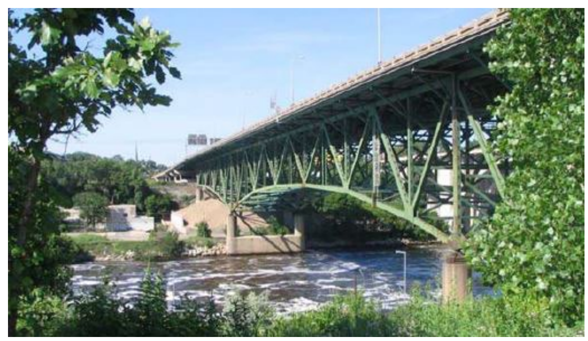

Figure C-78. I-35W Bridge Prior to Collapse (National Transportation Safety Board 2007)

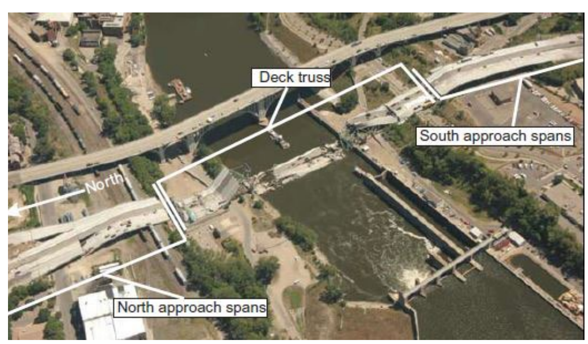

Figure C-79. Aerial View After the Collapse (National Transportation Safety Board 2007)

C.19.1.1 Event Response

First responders requested all available personnel to aid in rescue efforts. About 100 citizens helped first responders rescue those involved in the collapse. Local hospitals were notified shortly thereafter, and this was organized by the Hennepin County Medical center. Only 5 minutes after the first call, the Hennepin County Sheriff's Office had established a Unified Command Post in the parking lot of the nearby Red Cross facility, and they also set up a River Incident Command (National Transportation Safety Board 2007).

The day after the incident, the US Coast Guard established a security zone for the Mississippi River, and only emergency vessels were permitted to enter. Initial worries were of a terrorist attack, so it was ruled a crime scene by the Minneapolis Police Department. The Unified Command System implemented, per the rules of the city of Minneapolis, were deemed appropriate by the NTSB during analysis. Recovery efforts continued in the water until August 6th when the last victim was found. River traffic did not return to normal until October 6th (National Transportation Safety Board 2007).

C.19.2 Emergency Planning

C.19.2.1 Crowdsourcing and Information Gathering

The Minneapolis Fire and Police Departments were dispatched after a 911 call was received. The collapse was confirmed by MnDOT freeway cameras. Eyewitness testimony, a security camera captured collapse video, and a photograph from a commercial airline passenger, as shown in Figure C-80, were gathered after the incident to paint the picture of the collapse.

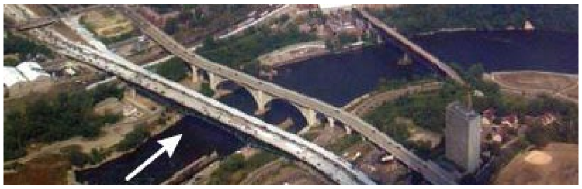

Figure C-80. Aerial View a Few Hours Before the Crash (National Transportation Safety Board 2007)

C.19.3 Assessment

The collapse was captured on a security camera from the Lower St. Anthony Falls Lock adjacent to the bridge. This video showed the south end of span 7 (the middle span) showing signs of failure first, indicating this region was the cause of the collapse. Because of this information, recovery efforts focused on that area for closer inspection.

The truss portions were removed from the river and later analyzed for defects or any other signs that could pinpoint the location of failure. The damage indicated the gusset plates were the initial location of collapse.

A passenger in a commercial flight captured a picture of the bridge a few hours before the collapse. This photo showed where construction crews and staging materials were located on the bridge. This in combination with eyewitness testimony was used to determine the exact location of these materials, as the extra weight was later suspected as part of the cause of collapse.

An analysis was performed on the suspected gusset plates after the collapse. Stress tests were conducted using the same demands that would have been imposed on the bridge at the time of failure. It was determined that several of the plates had a capacity less than the demand, some on the order of 2x less in the cases of shear. These deficiencies were not caused by an increased load on the bridge but were deficient for even the original design bridge loads (National Transportation Safety Board 2007).

C.19.4 Rapid Restoration

C.19.4.1 Contracting

After the collapse of the I-35 Bridge, the steps taken required immediate action to rebuild the bridge quickly. The first step in reconstruction was acquiring the land necessary to build. To expedite this process, the Minnesota DOT used a "two-step right-of-way acquisition." This allowed the DOT immediate access to the construction site as well as a guaranteed timeline for financial closure on each piece of land. To complete this project rapidly and to minimize any delays caused by permit constraints, a well-defined scope was needed. During the bidding process to select a Design-Builder, the MnDOT was highly interactive and conducted multiple one-on-one meetings with each competitor to keep ideas and designs confidential. The MnDOT also created a transparent evaluation plan with incentives for timely completion and success. The new I-35W bridge was completed 339 days after construction began, almost three months ahead of schedule. The bidding timeline is shown in Figure C-81.

Schedule Prior to Contract Award	
August 1	Bridge 9340 collapses
August 4	Mn/DOT issues RFQ
August 8	Five teams respond to RFQ
August 8	Mn/DOT short-lists five teams
August 23	Mn/DOT issues RFP
September 14	Technical proposals due
September 18	Price proposals due
September 18	Mn/DOT interviews design-build teams
September 19	Project letting
October 8	Contract executed

Figure C-81. Bidding Timeline (Hieptas 2008)

C.19.4.2 Design

The new replacement structure, called the St. Anthony Falls Bridge, was designed to maximize safety and quality with input from the local communities via a day long design charrette. The design team listened to the input from eighty-eight citizens and government official who helped decide on essential aesthetics features including the curved shaped piers and a signature lighting scheme for the bridge. The new bridge design placed a strong emphasis on reducing long-term maintenance costs and included several levels of structural redundancy and long-term structural health monitoring. Sensors were built into the bridge to broadcast real time information about the bridge performance and provide data during construction. The construction of this bridge took advantage of local labor, local materials, and used precasting techniques to minimize cost and reduce environmental impacts. Constructing most of the bridge on land reduced the amount of construction waste that entered the river (Chiglo & Figg 2008, Figg & Phipps 2008).

C.19.4.3 Permanent Structure

The new St. Anthony Falls bridge consists of twin concrete structures that are 1,223 feet in length and utilized two box girders in each structure. The 504-foot-long main spans used precast segmental construction techniques and the side spans were cast-in-place. Each concrete structure is approximately ninety feet in width and supports five lanes in each direction. The 120 precast superstructure segments varied in both length (thirteen and a half feet to twenty-five feet) and depth (eleven feet at midspan and twenty-five feet at piers). Eight long line casting beds were constructed on the existing I-35W roadway to fabricate the precast superstructure. The proximity of the casting yard streamlined transportation of the precast element and simplified the coordination between the construction crew and the engineering team (Figg & Phipps 2008).

The bridge foundation is composed of a total of 109 drilled shafts. The diameter of the shafts ranged from four to eight feet in diameter and were up to ninety-five feet deep. This foundation type was chosen to reduce the number of operations and reduce construction time. Four drill rigs operated simultaneously to complete the foundation as rapidly as possible. Self-consolidating concrete with a design strength of 5000 psi was used for the shafts to speed placement and ensure quality (Figg & Phipps 2008).

The four main pier footings spanned portions of the previous bridge's foundation, drainage tunnels, and existing utilities. The curing of these mass concrete footings was controlled using embedded cooling pipes and a custom concrete mix. Each footing supported two 70-foot concrete piers and two box girders. The curved shape of the piers matched the taper of the variable depth box girders (Figg & Phipps 2008).

Figure C-82. Placement of Main Span Precast Segments (Figg & Phipps 2008)

The box girder superstructure included cast-in-place side spans and a precast segmental main span that crossed the river. Construction operations of the side spans and precast main span segments occurred simultaneously to reduce the overall construction time. In addition, the eight long-line casting beds were operated simultaneously. Once the precast segments were constructed, they were transported and stored adjacent to the river until it was time to install them. Segments were then delivered to the site by barge and lifted with a barge-mounted crane as shown in Figure C-82. The 120 precast segments were erected in forty-seven days. Midspan closure pours connect the cantilever spans from opposite sides of the river. Each pair of adjacent precast segments were connected with a longitudinal closure pour. The entire bridge deck was transversely post-tensioned to add durability to the riding surface (Figg & Phipps 2008).

C.19.5 Challenges

MnDOT wanted to keep the scope of the bridge small and defined to stay within specific permitting limits through "Categorical Exclusion." This kind of permit allowed the DOT to complete small tasks without an environmental impact assessment. If MnDOT violated this permit, it would have resulted in an increased project duration. (Gransberg & Loulakis 2012).

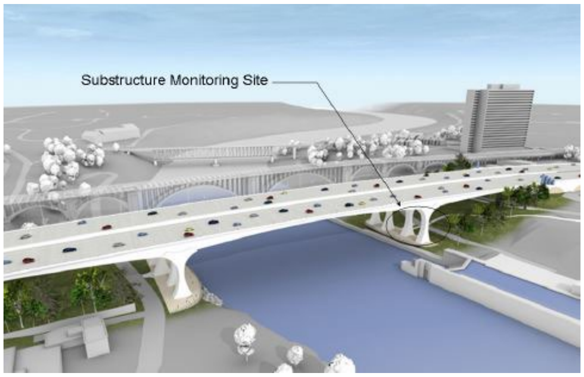

Figure C-83. Computer Rendering of Replacement Bridge (Collins et al. 2014)

C.19.6 Innovations and Lessons Learned

C.19.6.1 Inspection Guidelines

During routine load ratings, connections such as gusset plates should be evaluated, even though they are not part of the AASHTO standard procedure. Also, new bridges should be load rated, despite the lack of requirement by AASHTO as well. The implementation of hese two suggestions could have prevented the disaster altogether. Moreover, there is no clear national guidance on construction loads, which should be considered before any alterations or equipment is placed on a structure, and contractors are expected to have due diligence before starting work (National Transportation Safety Board 2007).

C.19.6.2 Structural Health Monitoring

Remote sensing technologies were included with the construction of the new bridge to enable better structural monitoring and preparation for another disaster, whether it be a collision or extreme weather event.

During construction thermal monitoring was used to monitor the curing of the mass concrete elements (i.e., drilled shafts and pier footings). These devices were placed on the reinforcement prior to pouring concrete, as shown in Figure C-83 and Figure C-84. Construction load monitoring was also used in the bridge during erection, which included strain gauges attached to the reinforcements. Lastly, long-term monitoring after the structure completion was implemented, including live load truck tests, deck corrosion, box girder vibration and strain monitoring. The results from the sensors have shown the ability to detect minute changes within the structure, which can be used to prevent a major emergency event such as another collapse (Collins et al. 2014).

Figure C-84. in Gauges on the Reinforcement of Replacement Bridge (Collins et al. 2014)

C.20 Rapid Repair of Sava River Bridge at Brcko 1996 [Man-made]

Table C-20. Rapid Repair of Sava River Bridge at Brcko

Case Study Name/Date	Sava River Bridge at Brcko (1996)
Location	Brcko, Bosnia
Event Type	Man-made (explosion)
Bridge Name	Sava River Bridge at Brcko
Scope/Costs	Three 20m spans and one 35m span; total cost N/A
Planning Techniques/Tools	Military Load Class Rating
Event Response	N/A
Assessment Techniques/Tools	Visual Inspections, Hammer sounding, and measurements
Rapid Restoration Type	Portable modular prefabricated panel truss (i.e., Bailey Bridge)
Innovations	• Use of panel trusses that rest on top of existing bridge substructures • Military Load Class Rating due to lack of bridge plans

C.20.1 Introduction

The historic Sava River Bridge at Brcko was built in 1894. The bridge was 800 m long and originally served as a railroad bridge until it was converted to vehicular traffic in 1985. The original bridge served as a major supply route, and it was destroyed from warfare in the 1990s by explosives, as shown in Figure C-85. In 1996, an international team of US military engineers and civilian contractors were sent to restore the partially collapsed bridge. The construction needed to be completed before winter weather arrived and the annual spring floods began. A modular bridge system was used to restore the bridge to temporary, one-way traffic. The rapid repair construction took place in 20 days.

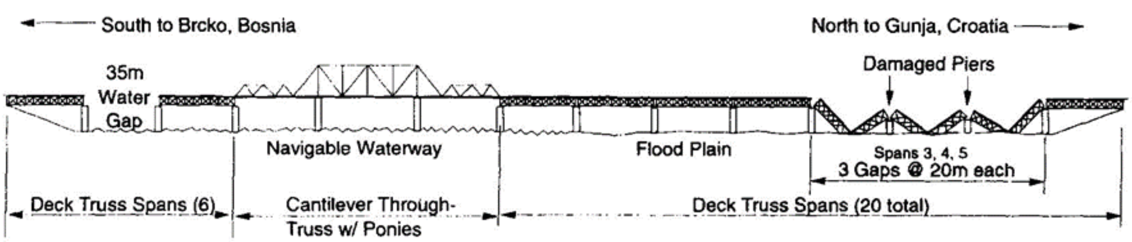

Figure C-85. Elevation of Save River Bridge at Brcko (with permission from ASCE, Mlakar & Ray 1997)

C.20.2 Emergency Planning

C.20.2.1 Crowdsourcing and Information Gathering

Bridge plans were not available, so military engineers had to rely on the local community to understand how the bridge functioned prior to damage, such as if the bridge experience any severe shaking or made noise during routine use. The use of public feedback on the bridge's performance after the construction was crucial to ensure the bridge was repaired properly.

C.20.3 Assessment

Initial inspections revealed several collapsed spans, but the full extent of the damages was unknown with a simple visual inspection. The bridge was load rated using the Military Load Class (MLC) procedure, which found that the bridge's capacity was limited by the 35m deck spans across the main river channel, which permitted the use of MLC 60, or a 60-ton vehicle with a single-way crossing. Subsequent findings of the 1985 bridge conversion from rail to roadway verified this load rating.

As the bridge was repaired, workers completed a more thorough visual inspection, and used hand tools to investigate any abnormalities. Using this method, crews found additional minor delamination damage, but nothing to require a change to the initial bridge assessment.

C.20.4 Rapid Restoration

C.20.4.1 Temporary Structure

Using a modular panel truss bridge system, a pony truss was built to cross the collapsed river span and three floodplain spans. The river span was a simply supported deck truss, and the floodplain spans were continuous spans with intermediate bents.

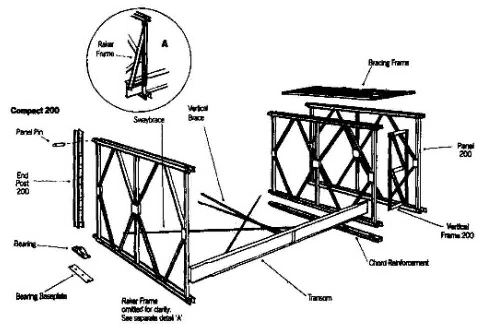

Figure C-86. Panel Truss System (with permission from ASCE, Mlakar & Ray 1997)

Bailey Bridge-like Panel Trusses were the specific type of trusses selected, as shown in Figure C-86. These were modular units that could carry up to MLC 100 ratings for lengths up to 61m. A double wide model was chosen with a single unit height, and the chosen MLC was a little bit greater than the MLC 60 rating. To use this system, two intermediate piers on the floodplain needed to be repaired, as they were damaged from the explosives. See Figure C-87 for the design details. Furthermore, they were too low to support the trusses, so they had to be raised in elevation. Steel was added for reinforcement and the concrete mix was catered to the harsh freeze-thaw climate for durability. High early strength was a requirement for the accelerated construction. Proper detailing was needed to ensure there was continuity between the old stone piers and the new concrete additions.

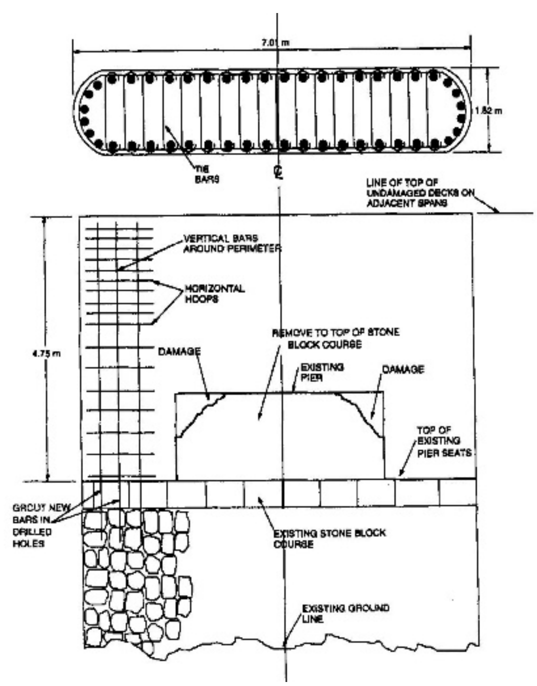

Figure C-87. Pier Drawings (with permission from ASCE, Mlakar & Ray 1997)

At the start of construction, the damaged sections were carefully dismantled as workers were still mindful of the potential for hidden mines. Concrete and steel had to be removed from the existing intermediate piers, and this was accomplished by using controlled explosives. US military engineers led the demolition.

Once the damaged sections were removed, civilian contractors repaired and raised the intermediate bents on the floodplain. The damaged masonry from the stonework was chipped off and reinforcement was added and grouted to ensure continuity between the new and old sections. Since construction took place in the winter, heat-insulated tents were used to provide stable curing conditions. Quality control was measured with slump tests, NDE hammer testing, and control cubes.

When the concrete reached the minimum strength threshold, the panel trusses were set. This task was completed by US and Hungarian military engineers. A representative from the panel truss manufacturer led the installation and provided guidance. The trusses were assembled on the road, then launched into place using a roller system, crane, and forklift. Using jacks, the panels were secured to their bearings. This process took about 10 days to complete, and the progression of work is shown in Figure C-88

A load test was conducted once the panels were set. An MLC 60 rated vehicle was driven across the bridge slowly, and military engineers visually inspected the bridge as it traveled across. They noted locations of deflection and other signs of distress. These results were compared to locals, who said the bridge performed roughly the same as it did before the war damage.

The bridge was opened to supply routes as soon as it passed the load testing. Proper signage denoted the one-way traffic and speed was monitored. Weekly visual inspections took place to ensure the bridge was performing as it should.

The panel truss designed was not designed to last forever. Once warfare halted, the panels could be removed and replaced with permanent trusses that support two-way traffic.

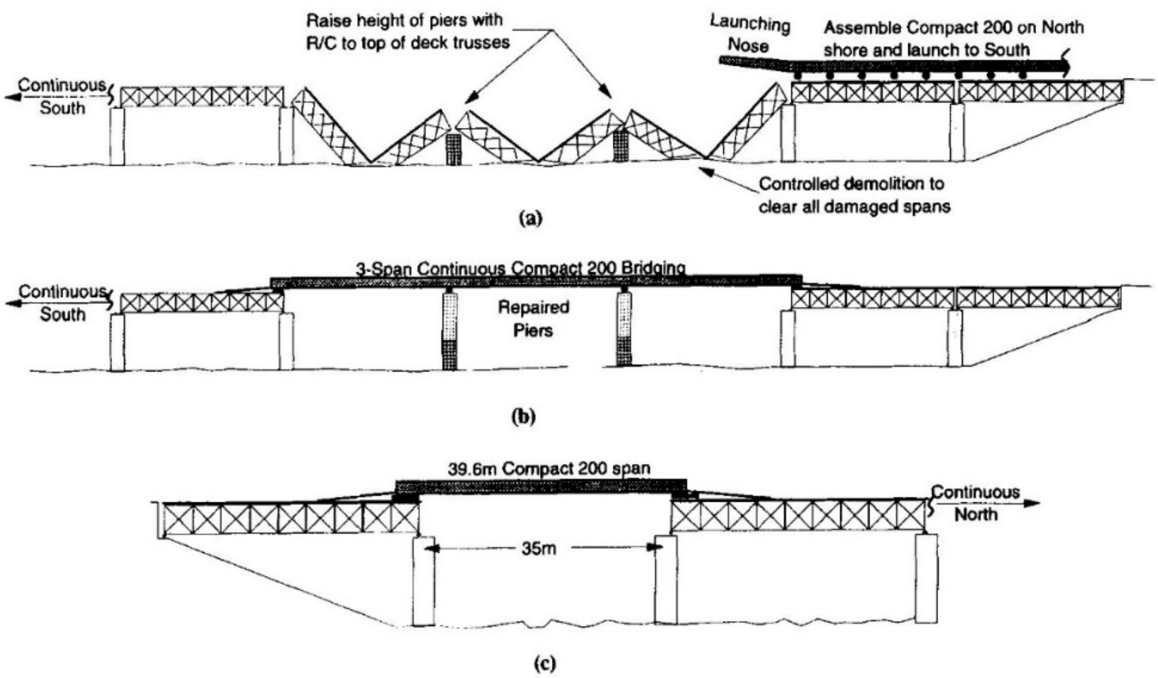

Figure C-88. Implementation Plan (with permission from ASCE, Mlakar & Ray 1997)

C.20.5 Challenges

When US crews arrived to repair the bridge, it was unknown if there were still mines present at the bridge. Troops had to inspect the area for explosives, but this was challenging as there was a couple feet of snow on the ground at the time. Workers had to be extremely careful at the site for the entire duration, as there was a constant threat of attack.

Since the bridge was in an active war site, the original bridge plans were not available. Measurements had to be taken in the field, and a preliminary estimate of the bridge's original capacity was made following the military classification procedure. This process mirrors typical load rating techniques, but it was greatly simplified for use by combat engineers. Allowable stress design was followed, but only the crews investigated the limiting elements on each bridge rather than analyzing the entire system. The final “result” was a standard military load class (MLC) that gave allowable weights based on tracked or wheeled vehicles.

Another challenge was the panel truss load path. These bridges were not designed to sit on the superstructures of an existing bridge. Combat engineers had to make special calculations to ensure the proper load distribution and verify this decision would not decrease the bridge’s capacity. The design of the panel trusses included an indeterminate “X” frame, so computer modeling was used to analyze the various maximum live load cases. Load patterns were considered using allowable stress design and mimicked both military and civilian uses. The computer models confirmed the design would carry the MLC 60 that could be supported by the existing bridge structure. As a precautionary procedure to maintain the structural integrity of the bridge, traffic was restricted to alternating one-way flow, and regulated by military police and with a lower speed limit was set.

C.20.6 Innovations and Lessons Learned

C.20.6.1 Implementation of Temporary Bailey Bridge

The use of portable modular prefabricated panel truss bridges that rest on the top of an existing bridge superstructure was not widespread before Sava River Bridge project. This paved the way for use of these systems in a simar manner and highlighted the need for further research in this area. Panel truss systems are a viable option for quick repairs, and should be considered for other situations, especially in war-time scenarios.

C.20.6.2 Military Load Class Rating

Using the MLC when bridge plans are unknown is an alternative method to determining the capacity of the bridge, even in its damaged state. This procedure could be applied after natural disasters, as it is simpler than the traditional load-rating processes.

C.20.6.3 Military Load Class Rating

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C.21 West Seattle Bridge 2020 [Immediate Action Inspection]

Table C-21. West Seattle Bridge

Case Study Name/Date	West Seattle Bridge (2020)
Location	Washington, USA
Event Type	Immediate Action Inspection
Bridge Name	West Seattle High-Rise Bridge
Scope/Costs	Full Bridge Closure for 9+ months; $225 Million
Planning Techniques/Tools	Continued long-term monitoring, worst case scenario planning
Event Response	Immediate Structure Closure, detours
Assessment Techniques/Tools	Long term monitoring, visual inspection
Rapid Restoration Type	Temporary shoring, Carbon Fiber wrapping, bearing replacement, epoxy-crack injection
Innovations	• Long term monitoring • Non-Destructive Testing • Simultaneous temporary and permanent repair design

C.21.1 Introduction

The West Seattle High-Rise Bridge was Seattle's busiest bridge, with over 100,000 vehicles traveling across daily (Seattle Department of Transportation 2020). Built in 1984, The 2600ft bridge crosses the Duwamish River and connects West Seattle to Harbor Island (Newcomb 2020). The bridge had been closely monitored since 2013, when shear cracks were first noticed during a routine inspection on the post-tensioned box girders. However, subsequent inspections found the cracks to be rapidly growing. On March 23rd, 2020, there was a sudden growth in cracks, prompting an immediate structure closure. Extensive detours were put in place to reroute traffic, including restricting modes of transportation on the adjacent Spokane Street Low Bridge for commercial and public transportation use, and rerouting commuters to other nearby bridges. The decision on whether the bridge should be repaired or replaced was evaluated while emergency repairs were underway. The City of Seattle decided to repair the bridge and postpone replacement a few months after the structure was closed (Seattle Department of Transportation 2020).

C.21.1.1 Event Response

Extensive detours were established once the bridge was closed. The Seattle Department of Transportation (SDOT) coordinated with King County Metro to redesign public transportation routes and maintain the flow of commerce and travel. Local first responders such as the Seattle Police Department and Fire Department were also coordinated with to ensure that the closure did not have adverse effects on response times in the area (Seattle Department of Transportation 2020).

As part of the detours, several local road improvements were also completed to help maintain traffic flow through the area. Remote adjustable traffic signals were installed at one intersection, which can be adjusted to accommodate changes in the detour routes or levels of traffic without having to send personnel on site. New bus lanes, pedestrian crossings, and modified travel lanes were also included in the project (Davis 2020c). The adjacent Spokane Street Low Bridge also underwent several improvements to ensure it would be able to handle the increase loading from heavy commercial vehicles and public transportation (Bergerson 2020b).

A task force was created, by utilizing pre-established unified response plans, which included the City of Seattle, the US Coast Guard, SDOT, and other local agencies.

C.21.2 Emergency Planning

In 2013, the first signs of distress were found on the West Seattle Bridge. Routine inspections scheduled for every two years were increased to annually after the 2013 inspection. In 2019 the inspection frequency was increased to 4 a year, as the cracks first discovered were worsening at alarming rates. Then in 2020, the bridge was inspected each month until the closure (SDOT Blog 2020b). The structure was originally built for 6 lanes in total and was later retrofitted to include 7. Furthermore, an estimated 80% of the structure's weight was attributed to dead load. These factors, compounded with increase vehicular weights over the years, caused the worsening of the cracks (Newcomb 2020).

In 2014, the Seattle DOT installed long term remote monitoring equipment on the affected beams and girders of the West Seattle Bridge to keep track of the width of the existing cracks first noted in 2013. The long-term monitoring showed that the cracks began to rapidly grow over the later part of 2019 and into 2020, leading to the closure order.

To aid in the structural assessment of the structure, SDOT hired a consultant to investigate the cracks. In February of 2020, the consultant recommended traffic be restricted on the bridge to only two lanes in each direction by the end of the calendar year. However, as the consultant refined their original analysis, they informed SDOT that the cracks were worse than first believed. From March 20-23rd, the bridge was visited daily, and on March 23rd, new cracks were found in areas previously denoted as "crack free". The ever-increasing cracks led to the immediate closure (SDOT Blog 2020g).

As more information was discovered about the worsening condition of the bridge, the task force began planning for a possible structure collapse. The growing shear cracks were of great concern, so three scenarios were planned:

1. Immediate Evacuation – indicates collapse is possible in a few days or hours
2. One to Five Day Notice – for anticipated failure as opposed to immediate failure
3. Controlled Demolitions – to maintain the safety of all parties involved, a date could be selected for the demolition

Along with the three scenarios described above, a "Fall Zone" was also outlined, and businesses and residences impacted by this region were notified of this possible danger. The designed "Fall Zone" included a buffer as well. Furthermore, in the event of a collapse by any of the three scenarios, access to Harbor Island could be cutoff altogether, so residences were told to prepare accordingly (Seattle Department of Transportation 2020).

C.21.2.1 Crowdsourcing and Information Gathering

SDOT used multiple communication platforms including AlertSeattle (push notifications), Wireless Emergency Alerts (texts), US Coast Guard Alerts (sirens from vessels and broadcasts to nearby ships), and Social Media Platforms to notify the public of event updates (such as Twitter, Facebook, and the City's Website) (Seattle Department of Transportation 2020).

C.21.3 Assessment

After the bridge was closed, further structural assessment was conducted. From these inspections, it was found that the bearing on Pier 18 were compressed and bulging. This indicated the bearing was restrained, which prevented the bridge from moving with changes in load. This in turn directs pressure on regions of the bridge that were not designed for such loads (Davis 2020a).

New long-term monitoring equipment was installed on the bridge in July. This new system was installed to improve the monitoring of the cracks and included a camera system to provide real time visual observation of the cracks. This new equipment found that the cracks did slow in growth once traffic was removed from the bridge, but still grew, although at reduced rates. The monitoring was vital to verify that the shoring and emergency repairs slowed the cracking, and provided more accurate indicators of further damage that may lead to a possible collapse. The sensors included with this equipment were movement sensors, which measure displacement in the horizontal and vertical direction, and crack monitors, which measure the width and slip of cracks. Cameras capture the growth of the cracks.

Nondestructive testing of several post-tensioned cables was also conducted to determine if these elements were damaged as well. Over 100 non-destructive tests were conducted over the course of the project, including Ground Penetrating Radar (GPR) to identify areas of corrosion in the post-tension tendons (SDOT Blog 2020f) Impact Echo (IE), and Ultrasonic Pulse Velocity (UPV) to investigate the tendons and depth. The results from the GRP found corrosion was not a concern of the tendons (SDOT Blog 2020a).

C.21.4 Rapid Restoration

C.21.4.1 Contracting

Once the required repairs were decided upon, SDOT sent out a Request for Information (RFI) to procure a contractor. In this process, SDOT also waived typical competitive bid procedures to expedite the process. The contractors who submitted proposals for the project were evaluated based on their work with the city on previous projects and their proposal contents. (Davis 2020f).

C.21.4.2 Design

At the beginning of the project, it was unclear if the structure needed to be repaired or replaced. While the more information was gathered on the bridge's structural integrity, emergency repairs were scheduled and completed. It was determined the emergency repairs would center on releasing the compressed Pier 18 bearings. Shoring was designed to strengthen the structure and prevent the development of other cracks until these repairs could be made, (Davis 2020a).

Meanwhile, a Technical Advisory Panel (TAP) was formed to determine the long-term repair or replacement of the structure. The panel consisted of experts in bridge engineering and construction, as well as those in geotechnical engineering and maritime industries. A community task force was also formed, as public input was also considered with the decision (Davis 2020d). As the decision was being made, a consultant was hired to design the replacement, as it was assumed the bridge would eventually be replaced, whether it was deemed the immediate solution or not. Other considerations for the solution included a tunnel instead of a bridge replacement (Bergerson 2020a). To help make the final decision, a cost-benefit analysis was used. This process looked at the benefits and drawbacks to either a total replacement or repair option. The criteria were heavily focused on the bridge's current structural assessment, user impact, and cost (Davis 2020b).

Ultimately, the Mayor of Seattle announced in November of 2020 that SDOT decided to progress the repair option as the long-term solution of the bridge's condition. The structure would eventually be replaced, so replacement designs continued (SDOT Blog 2020d).

C.21.4.3 Interim Repairs and Monitoring

To complete the stabilization of the structure with the Pier 18 bearing release, moveable platforms had to be installed below the bridge to provide a space for work crews. These platforms used the original holes that were patched during construction. These holes were used to hold the "form travelers" used to build the structure. The voids were reopened with core drills and other hydro demolition technical. All debris were captured in a vacuum system to prevent them from falling in the river below.

Next, the severely cracked portions boxed girders of the bridge were wrapped in Carbon Fiber, and then external posttensioning was added to the box girders, stabilizing structure, and making it safer for workers to then shift repairs to the damaged bearings. The post tensioning was placed inside the box girders, so only the anchor points were visible from the underside of the bridge.

After the first stages of stabilization was completed, crews were able to remove the damaged bearings. New rebar was added around the bearings, and new concrete joints were cast. Epoxy-injected cracks filled the array of cracks along the girders. Structural monitoring will continue until the permanent replacement is complete (SDOT Blog 2020d).

C.21.4.4 Permanent Structure

When the temporary repairs are completed, the focus of the project will shift to finalizing the permanent replacement of the West Seattle Bridge. The necessary funding needs to be obtained. The design process will include public input and environmental review.

C.21.5 Challenges

Funding was a major challenge for the project. SDOT considered federal, state, and local funding options, including grants, loans, and funding from the Washington State Legislature. Local funding sources were not popular (such as tolling), as the COVID-19 pandemic had already affected many local businesses and taxpayers. The ability to secure funding was a large motivator on the decision to repair versus replacing the structure in the near term. Repairs will allow more time to determine the best founding sources but may also increase the overall cost with higher future prices (Bergerson 2020c). The entire repair and replacement were estimated to be around $225 million. Ultimately, SDOT was able to secure an interfund loan to cover the initial emergency repairs costs, and then establish a Capital Improvement Program for the long-term solution (Davis 2020e).

C.21.6 Innovations and Lessons Learned

C.21.6.1 Long-Term Monitoring

The West Seattle Bridge project heavily relied on long-term monitoring equipment to gather real-time information on the bridge's structural integrity. Crack detection, movement sensors, and cameras all played a vital role in determining if the bridge should be repaired or replaced. This equipment also increases safety of the workers making the emergency repairs, and the surrounding public. The long-term monitoring equipment and frequent inspections were the reason the structure was flagged for closure, likely preventing a collapse while in service.

C.21.6.2 Detour Route Improvements

As the city of Seattle's busiest bridge, it was important SDOT developed a thoughtful detour plan. By working with regional public transportation groups, the city was able to limit the disruption to the public while still maintaining a high-level of safety. Restricting traffic on the Spokane Street Low Bridge helped maintain a short route for first responders and commerce in the area, and relieved some of the added congestion from nearby roads. Intersection reconfiguration and lane improvements across the region also helped keep traffic flowing. Smart technologies traffic signals that can be update remotely gave SDOT the ability to change traffic patterns as needed without having to send someone on site. All these improvements helped reduce the consequences of keeping the West Seattle Bridge closed for several months.

C.21.6.3 Cost-Benefit Analysis to Determine Course of Action

By using a cost-benefit analysis, the city was able to confidently make the decision to repair the bridge now and delay a total replacement off to the future. Gathering information from the 100+ non-destructive tests, long-term monitoring results, and technical experts, the bridge's structural integrity was then evaluated. Impacts to users and overall costs were also analyzed before the final decision was met. Completing this analysis while temporary repairs were being made helped save time, and provided the opportunity for a continued bridge investigation, as engineers discovered more information on the bridge's capacity while making repairs. For the safety of the surrounding area itself, the temporary repairs had to take place, and it was logical to do so during the discussion on the bridge's future.

C.21.6.4 Communication with Key Stakeholders

The establishment of several task forces and the inclusion of community involvement early in the process helped unite the city during this event. Since the West Seattle Bridge crosses the Duwamish Waterway, early involvement with the US Coast Guard was vital at understanding the unique requirements for ship traffic. Furthermore, updates through social media, push alerts systems such as AlertSeattle, and wireless emergency alerts were vital to keep the public informed of the constantly evolving event. Details about detour routes and areas impacted by the potential "Fall Zone" all helped keep the public informed, and to make it easier for people to plan accordingly, reducing overall disruption.

C.22 Franklin Ave 2015 [Other]

Table C-22. Franklin Ave

Case Study Name/Date	Franklin Ave (2015)
Location	Minnesota, USA
Event Type	Other
Bridge Name	Franklin Avenue Bridge
Scope/Costs	Complete Bridge rehabilitation with new deck, cap beams, abutments, piers, arch ribs, and railings; total cost of $43.1 million
Planning Techniques/Tools	Erection sequencing, pre-Acceleration Bridge Construction (ABC) site set up, partial bridge closure to remove the railing
Event Response	N/A
Assessment Techniques/Tools	Visual Inspection
Rapid Restoration Type	ABC to replace the deck, pier caps, ornamental railings, and restore other concrete components using precast concrete.
Innovations	• Using precast to replicate ornamental historic features • Prioritizing multi-modal use

C.22.1 Introduction

The historic Franklin Ave Bridge located in Minneapolis, MN was in disrepair and needed to be rehabilitated. A popular route for multi-modal traffic, the rehabilitation not only replaced deteriorated structural elements, but updated the structure for multi-modal use. Only closed sixteen weeks, the rehabilitation used ABC, as the arch design complicated staged construction, and temporary supports would dramatically increase costs and extend the project to two construction seasons. The bridge did have to close completely, but it was the best procedure to stay within schedule limits (Sivakumar 2017).

C.22.2 Emergency Planning

C.22.2.1 Crowdsourcing and Information Gathering

Public input was included in the rehabilitation design phase. The community wanted multi-modal transportation to be included with the design to accommodate pedestrians, bikes, and vehicles. The design team led open discusses with the community to ensure their desires were heard and needs addressed. The design ultimately settled on two thru lanes with a median separated bike and pedestrian paths (Sivakumar and Konda 2017).

Furthermore, a previous 1970 rehabilitation removed many of the historic components of the bridge. The public wanted to restore the historic details in the new rehabilitation, which included the railing, lights, columns, and pier overlooks (Sivakumar and Konda 2017).

When scheduling the construction timeline for the bridge, the public wanted a limited closure period so residents could enjoy the bridge for part of the summer months. Using ABC made this dream a reality, as the bridge was only closed for sixteen weeks (Sivakumar and Konda 2017).

C.22.3 Assessment

The Franklin Avenue Bridge went under a deep comprehensive investigation to examine the performance, durability, and historical importance in 2007. This test was recommended by the National Park Service Preservation Brief which implies that an inspection should be done to examine the durability of the concrete. This comprehensive exam included detailed surveys, delamination surveys, reinforcing bar cover surveys with the use of ground-penetrating radar, corrosion potential, concrete resistivity, and many other tests. After all these tests were conducted, it was determined that the bridge had widespread concrete deterioration it its abutments, piers, and arch ribs. The main cause of the deterioration was due to chloride corrosion. The concrete was exposed to a chloride-laden water that occurred due to deicing salts leaking through the expansion joints (Johnston 2017).

The Franklin Avenue Bridge was built in 1923 and was the world's longest arch bridge of its time. It was listed on the National Register in 1978 of historic bridges and voted a Minneapolis landmark in 1985. The bridge's design consisted of a 5-span open spandrel concrete arch bridge. The arch ribs were reinforced with steel Melan trusses (Sivakumar and Konda 2017).

Visual inspections revealed severe concrete deterioration, leaking expansion joints, and exposed reinforcement (Sivakumar and Konda 2017).

C.22.4 Rapid Restoration

C.22.4.1 Permanent Structure

To prepare for the ABC process, the deck panels, cap beams, and ornamental railings were all precast and brought to the site via barge. The proposed designed decreased the number of expansion joints from 15 to 6 to reduce the chances of deterioration. The deck panels were fabricated at the KNA Bohemian Flats yard, making 4-5 panels a day for a total of 350 panels. The panels were cured with steam and then pressure washed before transport. The panel production started a year before the actual ABC work due to the large quantity of panels. The 43 cap beams were manufactured in Elk River, MN, and all 163 ornamental railing panels were built in New Ulm, MN (Sivakumar and Konda 2017).

Before construction began, the utility rack and falsework were installed to prepare for the rehabilitation. Then, with a partial bridge closure, the 1970 railing was cut and removed from the bridge. Then, ABC was ready to begin (Sivakumar and Konda 2017).

The bridge was cut in the transverse direction using a saw, and pieces were removed and placed on a barge. The pier walls were removed, and then the new pier overhang was cast in place due to its curved geometry. With the overhangs curing, the cap beams were removed and then replaced, lowering them to the bridge with cranes. Grout was used to connect the cap beams to the columns. By day 19 of construction, the deck panels were ready to be set. These were slid into place using polytetrafluoroethylene (PTFE) and connected using Ultra High-Performance Concrete (UHPC) joints (Sivakumar and Konda 2017). A polyester polymer overlay was laid on top of the joints for added protection (Sivakumar 2017).

Next, the ornamental railing was placed, then pilasters were formed between each railing section after they were secured to the bridge. To cover the deck, pre-mixed polymer concrete (PPC) was spread. Once cured, the bridge was then opened to traffic (Sivakumar and Konda 2017).

C.22.5 Challenges

The UHPC joints did not fit together perfectly, as there were rebar conflicts with the closures. This common problem with UHPC joints stems from a lack of established project tolerances. Having a comprehensive QAQC plan to spot errors with congested joints, streamlines the installation process (Sivakumar and Konda 2017).

Around the same time of the concrete manufacturing of the numerous precast components, the Vikings Football stadium in Minneapolis was also under construction. This led to a concrete shortage and significantly higher concrete prices. To try and reduce costs, most of the precast components were shipped to the site via barge, and some were even fabricated close to the site to reduce transportation costs. Furthermore, some of the remnant piers were salvaged, reusing concrete (Johnson et al. 2017).

C.22.6 Innovations and Lessons Learned

C.22.6.1 Importance of Pre-ABC Planning

The team learned how valuable pre-ABC planning was to finish the project on time. Setting up the necessary equipment, making site preparations, and modeling construction sequencing are all ways the team can be prepared for construction and to reduce the likelihood of issues during construction (Sivakumar and Konda 2017).

C.22.6.2 Awareness of Historic Bridge Properties and Components

During the restoration, it was imperative that the construction team was familiar with the historic construction. Since historic concrete does not sound nor feel the same has new concrete, this increases the likelihood for structural damage as well as increase repair costs (Accelerated Bridge Construction University Transportation Center, n.d.b.).

C.23 I-84 Bridges 2013 [Other]

Table C-23. I-84 Bridges

Case Study Name/Date	I-84 Bridges (2013)
Location	New York, USA
Event Type	Other
Bridge Name	I-84 Bridges over Dingle Ridge Road
Scope/Costs	Total Replacement of 2 I-84 Bridges over 2 weekends and total cost $7.83 million
Planning Techniques/Tools	Permitting attainment and building temporary shoring for new structure to be built
Event Response	Maintaining NYSDOT website to keep the public informed
Assessment Techniques/Tools	Inspection Reports and visual inspection for existing structure, SRTT and OBSI for new structure
Rapid Restoration Type	ABC using hydraulic jacks to slide new bridges constructed alongside the existing bridges into place
Innovations	• Sliding bridges into place with Push Grippers • Using approach slabs as temporary spans before fill could be placed • Building new abutment around existing one to limit traffic disruption.

C.23.1 Introduction

The twin I-84 Bridges over Dingle Ridge Road had deteriorated and needed to be replaced. Located in southeast New York, these bridges had an ADT of 75,000, and served a vital role for commerce in the area. The state of New York decided to use Accelerated Bridge Construction (ABC) for the project to reduce traffic disruption, impact to the surrounding watershed, and to reduce construction costs. By using this technique, they were able to save approximately $2.7 million. These savings accounted for more than 20% of the original cost of the bridge without Accelerated Bridge Construction (Bhajandas et al. 2014). The new bridges used a Northeast Extreme Tee (NEXT) beams with precast approach slabs and an Ultra High-Performance Concrete (UHPC) closure pour on top of new bents. New York was satisfied with the result and began investigating what other bridges it could replace using this method (Sivakumar 2017).

C.23.1.1 Event Response

Clear communication to the public was key throughout the process. Notice of closures and delays helped reduce the traffic during the time of the closure by about 40%. Updates were issued from the NYSDOT website. A detailed timeline was initially released and included updated photos and current traffic conditions (Bhajandas et al. 2014).

C.23.2 Emergency Planning

C.23.2.1 Crowdsourcing and Information Gathering

The state of New York knew it needed to replace the twin I-84 bridges, but it did not know the best method of the replacement. As decisions regarding the construction procedure were underway, the team investigated the permits and other requirements for the project. Due to its location in the New York City watershed, extra precautions were mandated. Moreover, a site survey revealed the bridges had an elevation difference of 15' between them, complicating the proposed temporary bridge method to carry the traffic of one bridge during construction. The use of traditional construction methods with its temporary structure and crossover system would cost about $2 million more on top of the price for the new bridges and take two years. However, with ABC, the project would only affect traffic for two weekends using a slide-in approach, and greatly reduce the impact on the watershed. Thus, the team decided to use ABC for this project (Bhajandas et al. 2014).

C.23.3 Assessment

The original twin bridges were built in 1967 and were 140 feet long length and 33.3 feet wide. The eastbound bridge had a sufficiency rating of 62.0; the westbound bridge had a rating of 60.2. In addition, the bridges had other structural deficiencies that needed to be addressed, as revealed by inspection reports. Temporary steel supports were put in place on both bridges to prevent web crippling. Leaking joints severely damaged the bridge, and the deck wearing surface had worn asphalt. Lastly, approximately 25% of the steel girders were significantly rusted, as noted by a visual inspection (Bhajandas et al. 2014). An image from demolition is shown in Figure C-89.

Figure C-89. Bridge Demolition (Bhajandas et al. 2014)

Once the construction of the new bridges was complete, they were re-evaluated. The roadway quality was tested using the onboard sound intensity (OBSI) technique prescribed in AASHTO. The test conducted was a standard reference test tire (SRTT). To test for roadway smoothness, a high-speed inertial profiler was used. The new bridge surfaces were deemed an improvement from the existing bridges (Bhajandas et al. 2014).

C.23.4 Rapid Restoration

C.23.4.1 Permanent Structure

The first stage of the project was the Pre-ABC period. During this stage, the new abutments were built on the drilled shafts, concurrently with the superstructure built adjacent to the bridge on temporary piles. The second stage was the ABC period, where one direction of traffic was closed to demolish the existing bridge and to slide the new spans into place. The last stage was the post-ABC period, where flowable fill was added under the approach slabs, the temporary supports were removed, the wingwalls were added, and the final approaches were completed (Bhajandas et al. 2014).

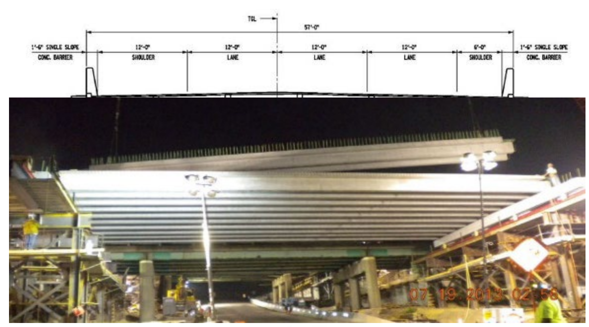

Figure C-91. Beam Installation (Bhajandas et al. 2014)

While the original structure was still in operation, the piles for the new bridge were drilled on the outside of the existing footprint. This minimized traffic impact and provided a stable foundation to place the substructure. A total of eight shafts were drilled, two on each abutment. The castings were 6 feet in diameter. The substructure consisted of a saddle bent abutment, which comprised of a cap beam supported by the drilled shafts and sliding shoes under the diaphragm. For the new spans' construction, these components were erected on steel temporary piles equipped with slide tracks, which were located at each bent (Bhajandas et al. 2014).

The cap beam had polytetrafluorethylene (PTFE) sliding bearing pads to support the end diaphragm. The cap beam was placed on top of the drilled shafts followed by the diaphragm, as shown in Figure C-90. These were originally set on the temporary bents and were later slid into place. Once in place, the NEXT beams were lowered to sit on the cap beams, as shown in Figure C-91. The deck reinforcement was epoxy coated on the bottom and stainless steel on the top. UHPC with steel fibers was used to close the joints, due to the “Buy America” clause in the contract, which limited the material that could be purchased, as shown in Figure C-92 (Bhajandas et al. 2014).

With the joints sealed, the deck was blast cleaned to prep the surface for the primer and rubber waterproofing layers (Bhajandas et al. 2014). The bridge was then ready for the lateral slide, as shown in Figure C-93.

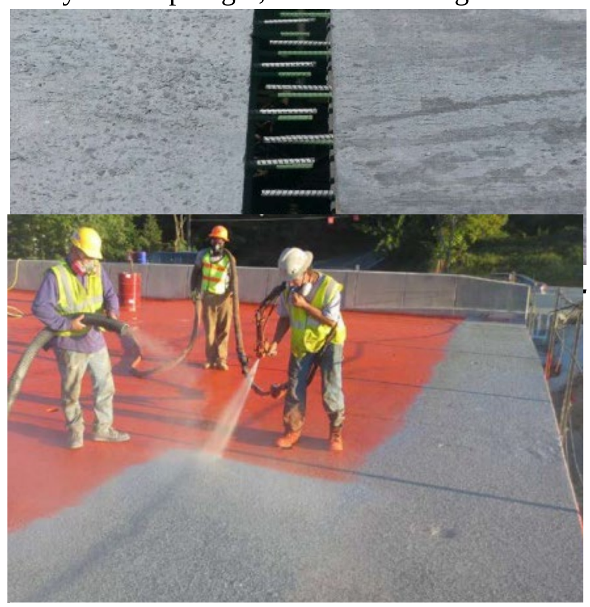

Figure C-93. Waterproofing Spray (Bhajandas et al. 2014)

For the ABC stage of the project, a prequalified contractor managed the operations. The contractors used their expertise to select the best method for moving the structure, whether it is with Self Propelled Modular Transporters (SPMTs), rollers, or jacks. In this instance, the Push Gripper was selected. One was placed at each diaphragm to push the bridge into place using hydraulics. The bridge slid across PTFE bonded to elastomeric pads, which had a friction coefficient of only approximately 8% (Bhajandas et al. 2014).

When it was time to slide the westbound bridge, the existing bridge was demolished as soon as the road was closed. Over twenty hours, the bridge was demolished, debris removed, and the new structure was slid into place. For the eastbound bridge, this process was accomplished in seven hours, as the contractor was more experienced with the second slide (D'Amico 2013). The slide moved both the bridge and the approaches to reduce closure time. With this design, the approaches acted like end spans, and then once in place, fill was poured in underneath them to create a single span design. The approaches were designed to carry traffic loads, as they would temporarily do so until the fill was able to be added (Bhajandas et al. 2014).

During the westbound (first) slide, one of the Push Grippers advanced quicker than the other, causing the bridge to fishtail and bind. This was attributed to heavy rains at the time and poor communication between workers. This error was later corrected for the eastbound slide, which was accomplished without incident (Bhajandas et al. 2014). See Figure C-94 for a view of the Push Gripper and Figure C-95 for an image of the slide from the ground.

The new bridge design raised the underpass two feet for extra clearance of vehicles on Dingle Ridge Road. To accommodate this, the approach slabs design included a fairly steep angle, but this allowed for asphalt placement simultaneously, specifically in the built-up areas before the approach. With the asphalt laid, the bridge was striped and then was reopened to traffic (Bhajandas et al. 2014).

Dingle Ridge Road closed right before the slide and remained closed for a few days after each bridge move (Bhajandas et al. 2014).

Figure C-94. Push Gripper Installation (Bhajandas et al. 2014)

C.23.5 Challenges

The underpass road, Dingle Ridge Road, had a steep grade of about 16%. Furthermore, the eastbound and westbound I-84 lanes were at different heights due to the steep topography. Because of this, two platforms, each at their own height, had to be constructed to hold the new spans during the ABC phase (D'Amico 2013).

A tough permitting process because of the nearby watershed was also lengthy, and other requirements such as the "Buy America" clause in the contract required materials to be American made. These obstacles were easily overcome, but more time should be set aside before the construction begins to ensure all the details are ironed out to prevent delays.

Figure C-95. Slide in of Bridge (Bhajandas et al. 2014)

C.23.6 Innovations and Lessons Learned

C.23.6.1 Keeping the Public Informed of Closures

Looking back at the finished project, the New York Department of Transportation found the two-weekend closures were an adequate amount of time to complete the lateral slide operations and the public was provided sufficient notice, so they did not observe significant traffic disruption. Public outreach was partially to thank, and the frequent updates to the website was also accredited (Bhajandas et al. 2014). For a nearly completed project image, see Figure C-96.

Figure C-96. Aerial View of Construction Site with Nearly Completed Bridges (Bhajandas et al. 2014)

C.23.6.2 Requiring Key Personnel to Remain On-Site

It was found that key decision makers, such as engineers and contractors should be present on site to address any problems that arose (Bhajandas et al. 2014).

C.23.6.3 Complete all Contracts Before Construction

Contracts should be thorough and complete before construction begins to ensure the job description is detailed and accurate. Any discrepancies can take valuable time to sort out, and any missing information will only be magnified due to the compressed timeline (Bhajandas et al. 2014).

C.23.6.4 Slide-In Placement Procedures

When it came to sliding the bridges into place, a conservative value for the coefficient of friction should be used to account for unforeseeable events, like poor weather conditions, that will impact the coefficient (Bhajandas et al. 2014). See Figure C-97 for an image of the slide.

It is extremely important to monitor the slide. Several workers should be only assigned the task of monitoring the pressure readings and measurements to ensure the bridge is shifting uniformly to prevent binding. Negligence could cause damage to the components and decrease the overall structural integrity (Bhajandas et al. 2014).

Figure C-97. Sliding of Approach into Place (Bhajandas et al. 2014)

C.24 Keg Creek Bridge Replacement 2011 [Other]

Table C-24. Keg Creek Bridge Replacement

Case Study Name/Date	Keg Creek Bridge Replacement (2011)
Location	Iowa, USA
Event Type	Other
Bridge Name	Keg Creek Bridge
Scope/Costs	Demo and Repair of Bridge in 16 days (2 days late), total cost $2.67 million
Planning Techniques/Tools	Built a fabrication yard adjacent to the bridge to manufacture precast components before demolition to reduce traffic impact
Event Response	N/A
Assessment Techniques/Tools	Inspection Reports
Rapid Restoration Type	ABC with prefabricated components
Innovations	• Prefabricated rolled steel girders with concrete deck + railing • Fabrication lot on-site • Culverts to divert water and create a dry working area • Post-tensing and UHPC combination to prevent joints from cracking

C.24.1 Introduction

This study focuses on the Keg Creek Bridge Replacement project conducted by the Iowa DOT. The original Keg Creek Bridge was built in 1953 with a narrow roadway of only 28'. The continuous concrete 3-span bridge was classified as structurally deficient (Evans 2017).

The Iowa DOT weighed the pros and cons of using Accelerated Bridge Construction (ABC) to replace the existing bridge. Using traditional construction methods, the project was estimated to have a 6-month closure with a 14-mile detour. However, with the use of ABC, the project would only take about 14 days – significantly reducing the impact to the public.

Figure C-98. Existing Bridge (Used with permission © Iowa Department of Transportation, Evans 2017)

The Iowa DOT decided to pursue the ABC process for this 3-span bridge with jointless construction and pre-decked steel beams. The project cost $2.67 million and included a $22k/day incentive/disincentive with the 14-day schedule. The bridge was completed in 16 days using prefabricated components built adjacent to the bridge, and the Iowa DOT was overall satisfied with the outcome (Sivakumar 2017). See Figure C-98 for an image of the existing structure.

C.24.1.1 Event Response

The Keg Creek Bridge Replacement project received funds from Highways for Life (HFL) for $600,000 and the Transportation Research Board's Strategic Highway Research Program 2 (SHRP2) funds of $250,000 which greatly reduced the overall cost to the Iowa DOT (Sivakumar 2017). Keg Creek was chosen as a part of a study to investigate the viability of ABC, and more specifically, with a precast modular structure and precast approaches. Moreover, the 3-span system was chosen to better represent other bridges in the area, providing the opportunity for this bridge to serve as a demonstration for the state of Iowa.

C.24.2 Emergency Planning

C.24.2.1 Crowdsourcing and Information Gathering

Past Iowa bridge case studies were used as examples to determine the best options for the project. The use of ABC was relatively new to Iowa, but other rapid repair technologies were not. The agency decided to pick and choose rapid methods from other projects to serve as a model for this case. Typically, the Iowa DOT used concrete overlays with precast panel bridges. But for this project, an overlay would add weeks to the duration. The Iowa DOT had experience with Ultra High-Performance Concrete (UHPC) with other projects to create an impenetrable and stronger joint. However, they did not have experience using preassembled rolled steel girders but likened some characteristic to other projects with the more typical assembled on-site girders. This helped prepare the Iowa DOT for the Keg Creek Bridge replacement. This project was the first one that Iowa DOT conducted with the use of steel girder/concrete deck modules jointed on site with UHPC (Littleton & Mallela 2013).

C.24.3 Assessment

The original Keg Creek Bridge was built in 1953 with a narrow roadway of only 28'. The continuous concrete 3-span bridge had a sufficiency rating of 33 (structurally deficient), so the Iowa DOT knew it was time to replace the structure (Evans 2017).

C.24.4 Rapid Restoration

C.24.4.1 Procurement

All precast units for the bridge were cast at the on-site fabrication lot adjacent to the bridge, as shown in Figure C-100. This saved a significant amount of time and money for the project. High Performance Concrete (HPC) with a strength of 5,000 psi and mild epoxy coated reinforcement was used for the precast. The fabrication lot was divided up by the different bridge components, such as columns, approach slabs, deck, and abutments. However, due to convenience, the pier cap was cast in the dry stream channel before demolition. To fabricate the girders, the steel was first manufactured at a plant, then brought to the jobsite. Temporary wooden bents were constructed at the on-site fabrication lot, and the steel girders were set into place. Then, forms were used to create the composite steel/concrete girders. Similar to cast-in-place techniques, the concrete was supported by the girders during curing (Evans 2017).

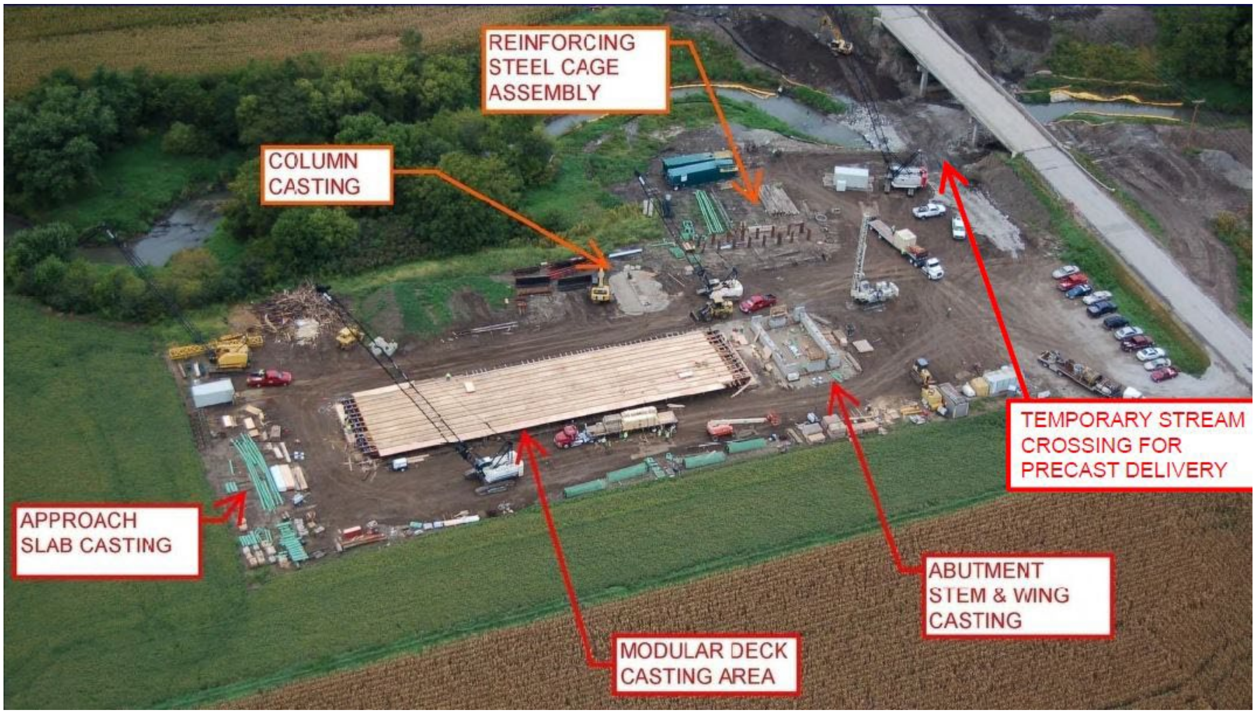

Figure C-100. Aerial View of Fabrication Lot (Used with permission © Iowa Department of Transportation, Evans 2017)

Figure C-99. Aerial View of Construction Site with Culverts (Used with permission © Iowa Department of Transportation, Evans 2017)

C.24.4.2 Permanent Structure

Before the existing bridge was demolished, drilled shafts for the new bridge were bored and filled with concrete and reinforcement (Iowa Department of Transportation n.d.). Concurrently, the necessary culvert implementation for the stream diversion was built to create a dry workspace for cranes and other equipment, as shown in Figure C-99 (Evans 2017).

From here, the existing bridge was closed to traffic, and the demolition began. It took two hydraulic breakers only 1 day to complete with the help of a wrecking ball. The newly bored drilled shafts and pier caps were protected to ensure they were not damaged by falling debris (Evans 2017). Next, the abutment piles were driven and grouted, allowing for the placement of the precast abutment components. The intermediate precast columns and pier caps were also set at this time, as shown in Figure C-101. The columns were placed on a sponge rubber bed to hold the grout in place. The abutments used a semi-integral design which provided room for expansion or contraction of the superstructure. It also was easy to set the superstructure into place, and thus worked seamlessly for rapid construction

Figure C-101. Pier Cap Placement (Used with permission © Iowa Department of Transportation, Evans 2017)

techniques (Iowa Department of Transportation and Sivakumar 2017). Self-consolidating concrete was used in the abutment assembly to finish off the pile caps. Anchors and bearings were installed on both the abutments and the bent caps. From here, the precast wingwalls were installed (Evans 2017).

With the abutments in place, the precast girders were set with two cranes. UHPC was used to close the transverse deck joints between spans, as this allowed for full moment transfer and did not require transverse post-tensioning. The closures were only 6” wide, creating low permeability (Sivakumar 2017). From here, the wingwall joints were sealed with self-consolidating concrete and UHPC was used to close the longitudinal joints between girders (Evans 2017).

With the bridge completed, the precast approach panels were set, and joints sealed with self-consolidating concrete. The superstructure was then post-tensioned, with tendons placed through pre-drilled hangers and holes on the exterior of the steel girders above the intermediate bents. The deck and approaches were ground down for a smooth riding surface, and then the bridge was opened to traffic. Riprap and other scour measures were installed after the bridge was reopened (Iowa Department of Transportation n.d.).

C.24.5 Challenges

The use of hairpin joint bars made it difficult to assemble the precast pieces, as the curved bars were hard to align, as shown in Figure C-102. The contractor recommended future use of straight bar ends for UHPC bonding to avoid fit problems and misalignments. Furthermore, the joints were often congested, and any adjustment to the hairpins to allow for a proper fit ran the risk of damaging the epoxy on the bars. The UHPC joints are critical, as they are what hold the bridge together. Any cracks can lead to freeze-and-thaw damage, so it is imperative there is clear communication between the manufacturer and workers. The UHPC joint at the abutment was difficult to form, so the UHPC leaked under the backwall, which created a mess. Figure C-103 shows the pouring of a UHPC joint.

Figure C-102. Hairpin Fitting Challenge (Used with permission © Iowa Department of Transportation, Evans 2017)

Figure C-103. UHPC Poured into Place (Used with permission © Iowa Department of Transportation, Evans 2017)

C.24.6 Innovations and Lessons Learned

C.24.6.1 Stream Channel Access

Having access to the stream channel was one of the best decisions made for this project. Culverts were constructed before demolitions to allow for easier access. This permitted the use of the channel for equipment, a spot for precasting the pier caps, and assembling the components (Evans 2017).

C.24.6.2 On-Site Fabrication Lot

The fabrication lot next to the bridge also streamlined the process and reduced overall costs. Special permits were not needed for large pieces, as there was no travel required on public roads. However, the contractor was not a fan of the precast approaches, as the subgrade had to be at the proper elevations for a smooth finish. This precision takes time, and they would recommend using typical cast-in-place approaches for future ABC projects (Evans 2017).

C.24.6.3 UHPC Joints

The use of UHPC over a pier cap had not yet been investigated before this project. The high loads could create cracks and debonding from the steel, which could later turn into leaking joints. Tests were conducted to determine if UHPC could be used in this capacity. The results found that adding post-tensioning rods would limit the likelihood of the joint from debonding and cracking, so this was added to the design, as shown in Figure C-104. During installation, all the rods were stressed simultaneously for an even load distribution (Evans 2017).

Figure C-104. Post-Tensioning over Pier Cap (Used with permission © Iowa Department of Transportation, Evans 2017)

The abundance of forms should be considered during the procurement phase. Mass production of the forms from a carpenter should be purchased to reduce the time required for workers to assemble forms on site (Evans 2017).

C.24.6.4 Inspection

Inspectors should be familiar with ABC process, and if needed, complete training on how to inspect ABC projects. The simultaneous construction and rapid progress may be overwhelming and/or alter the typical steps of work, confusing the inspector. This should be considered with future projects (Evans 2017).

The inspectors should be on site for many project milestones, including the column placement on the bed, and its subsequent grouting. Poorly formed footings could lead to structure collapse (Evans 2017).

C.24.6.5 Length of Construction

The project took 2 days longer than expected. Weather, flooding, and a litany of other factors could contribute more to such delays in the future. It was recommended to add a “grace period” to the contract to account for these unknowns, especially with such an accelerated schedule. This will reduce the pressures off the contractor and provide a built-in buffer (Evans 2017).

C.25 Salt Lake City Olympics ABC 2002 [Other]

Table C-25. Salt Lake City Olympics ABC

Case Study Name/Date	Salt Lake City Olympics ABC (2002)
Location	Utah, USA
Event Type	Other
Bridge Name	One bridge is not selected for this report[0]
Scope/Costs	Considered ABC for all Bridge Projects (hundreds of bridges)
Planning Techniques/Tools	Pre-event workshops to develop ABC standards and details
Event Response	N/A
Assessment Techniques/Tools	N/A
Rapid Restoration Type	Accelerated Bridge Construction
Innovations	• Precast components • Self-Propelled Modular Transporters (SPMT) specifications to limit cracking and dynamic loading • Guidelines to regularly inform management • Though not directly related to a specific emergency event, the processes developed are relevant to large scale events that require the use of ABC. Serves as a “mock” scenario.

C.25.1 Introduction

To prepare for the 2002 Olympics, Utah DOT (UDOT) used Accelerated Bridge Construction (ABC) to prepare its infrastructure for the influx of visitors as well as to showcase the state-of-the-art technology at that time. This push for ABC was a success and by 2010, ABC became standard practice for all cases where it was deemed practical and cost effective. Examples of ABC projects are shown in Figure C-105 and Figure C-106.

Figure C-105. Installation of Precast Element (Culmo 2011)

C.25.2 Emergency Planning

C.25.2.1 Crowdsourcing and Information Gathering

The mass implementation of ABC was relatively new for the UDOT so after each completed project, they distributed questionnaires to the public for feedback. In most cases, respondents were nearly equally split between satisfied, not satisfied, and indifferent. Analysis of these responses determined that those responding negatively were not satisfied with the project overall, not specifically the use of ABC.

Figure C-106. Precast Slab Placement (Culmo 2011)

For one project, a Likert 7-point polling system was used, and results were compared to a non-ABC project. Over 97% saw the ABC project as a success and rated it 3 or higher. UDOT utilized these results during Utah's legislative session to secure more funds. As a result of this demonstrated success, Utah has continued to see increases in transportation funding in recent years despite times of fiscal restraint.

C.25.3 Assessment

Information on structural assessment was not found. In most cases bridges that were replaced were replaced to add capacity rather than due to structural considerations.

C.25.4 Rapid Restoration

C.25.4.1 Design

With many of the ABC projects for UDOT, design standards, specifications, and details were all implemented to speed up the overall process. Prior to the mass implementation, UDOT hosted several workshops to develop these standards. Groups such as the Utah Association of General Contractors (AGC), American Council of Engineering Companies (ACEC), and Precast Prestressed Concrete Institute (PCI) were present to share their input and to create a cohesive plan.

Figure C-107. Bridge Slide-In Installation (Culmo 2011)

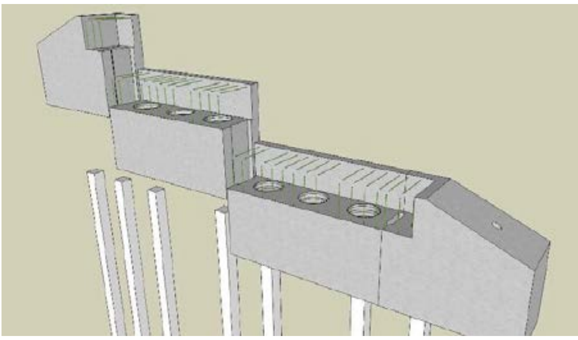

Figure C-108. Integral Abutment Design (Culmo 2011)

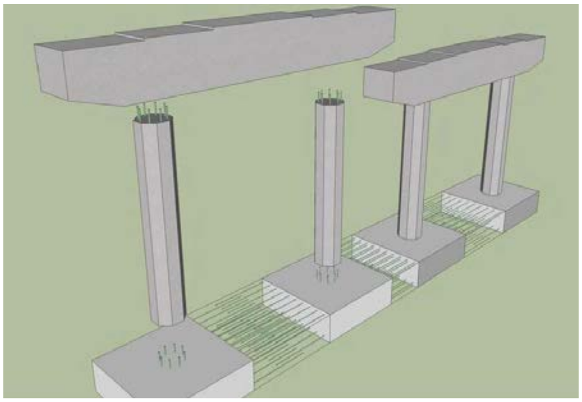

Figure C-109. Open Frame Bent Design (Culmo 2011)

C.25.4.2 Permanent Structure

Depending on the site, UDOT uses lightweight concrete for its ABC projects, as the state's soil contains significant deposits of Bonneville clay, which puts structures at a risk for settlement. The lightweight concrete reduces this risk, which helps with seismic design but also makes it easier to use Self Propelled Modular Transporters (SPMTs), or other similar processes (Figure C-107), to slide the bridge components into place. However, Utah does not have any requirements to use overlays on lightweight concrete, so in other states this may add additional time to the overall project.

Utah also uses cast-in-place closure pours, especially around abutments. The superstructure can be built out of precast girders or slabs, and Utah has several published standards for precast deck panels that act like a one-way slab. These slabs are supported by beams with prestressing or mild reinforcement. For bents and intermediate supports, open frame bents are popular but can be challenging to erect (Figure C-108). Prefabrication of these components offsite, and then transporting them in to be assembled on site saves time and money. To meet seismic requirements, Utah implemented a grouted splice coupler to achieve the same seismic benefits as a cast-in-place concrete. In essence, this design allows the bars protruding from one element to "plug in" to the voids in another. Then the connection is grouted with high strength grout. This design is similar to a lapped splice and can be applied in the same fashion to other components such as wingwalls, abutments, and footings.

For abutments, UDOT developed standards for an integral abutment design (Figure C-109). This method uses vertical shear keys with grout, and when combined with transverse reinforcement to distribute the load, the system can withstand the internal pile and other geotechnical forces.

C.25.5 Challenges

The use of precast components requires several joints across the length of the bridge, often resulting in joints that reduce the ride quality. Diamond grinding reduces the bumps but is not as smooth a typical cast-in-place deck because it removes the fine aggregate and exposes the coarse aggregate. It also renders the surface more prone to freeze-and-thaw.

Another issue with prefabricated components occurs with the railing. An exterior girder may end up carrying a greater load with the addition of the precast parapet railing than if it were cast-in-place. This extra dead load must be considered in the original design. Uniform torques applied to all bolts attaching the railing to the girders can also help distribute the load to the interior girders as well.

Figure C-110. SMPT on I-80 Bridge Replacement (Culmo 2011)

When using SPMTs to move superstructure components into place (Figure C-110), internal stresses (often unaccounted for) induced by the dynamic motion may adversely impact the structure. To test the impact of this movement, Utah State University attached strain gauges to different superstructures during the SPMT process at the beginning of the 2002 ABC push. They concluded that an additional dynamic load allowance of approximately 15% of the dead load should be included during design to prevent any major issues. They also found that that torsional effects during transport were negligible, but only if the bridge was wrapped properly and movements were maintained within specified tolerances. Furthermore, the use of SMPTs often equates to large overhangs of spans during the move. Utah found that its original rule of support at third points led to damaged parapets and cracks in the deck. To reduce cracking, overhangs were limited to only 20% of the overall length.

Figure C-111. Closure Pour Crack (Culmo 2011)

Often, high strength closure pours are specified for ABC. This is required to meet the early-strength requirements for a speedy construction, but these mixes often lead to cracking due to drying shrinkage (Figure C-111). Specifying lower strength concrete can help solve this problem and reduce cracking potential. However, DOTs must be sure to check their requirements for closures because, for traditional cast-in-place projects, the concrete strength may be significantly higher and often specifications do not change between cast-in-place and precast.

C.25.6 Innovations and Lessons Learned

C.25.6.1 Organizing Management for ABC

As Utah gained experience and expertise with ABC, they developed a flow chart showing the steps taken that led to their successes. UDOT found that regular communication with both upper management and politicians on ABC projects not only helped secure funds for further ABC expansion in the next legislative round, but also gain support from the public. Middle management should also be informed, and an open dialogue between the contractors, engineers, and management should always be implemented. The speed of construction often leads to more questions up front and during construction, thus delays can be prevented if the key players shift to an “on-call” role. Honest communication and explaining the successes and challenges provide the foundation for transparency.

C.25.6.2 Stakeholder Buy-In

There are several advantages of ABC that are important to share with stakeholders. First, it greatly reduces traffic impacts and delays and is safer for both workers and the public, as most construction takes places away from travel lanes. Furthermore, ABC may cost more up front, but in the long run, it generally saves a considerable amount of money. Lastly, higher quality bridges can be built, as the precast components can be manufactured in a controlled environment, away from harsh weather conditions and other uncontrollable factors.

C.26 State Route 30 & Bessemer Ave 2015 [Other]

Table C-26. State Route 30 & Bessemer

Case Study Name/Date	State Route 30 & Bessemer (2015)
Location	Pennsylvania, USA
Event Type	Other
Bridge Name	State Route 30 & Bessemer Ave
Scope/Costs	$2.3 million
Planning Techniques/Tools	Pro Team Meetings and Constructability Meetings, BIM to sequence construction events and check component fit
Event Response	N/A
Assessment Techniques/Tools	Lidar scan to generate as-builts since limited bridge knowledge was available
Rapid Restoration Type	ABC with precast steel composite slabs, new abutment cap, and precast approaches
Innovations	• Lightweight concrete to reduce component weights • Revit to sequence construction events

C.26.1 Introduction

The State Route 30 & Bessemer Ave bridge in Pennsylvania was a unique challenge to engineers. The bridge had limited as-built information, and the lack of a viable detour route meant the construction needed to be completed rapidly to reduce traffic impact. Moreover, the bridge had both a skew and a curved alignment. The project used Accelerated Bridge Construction (ABC) to remove and replace part of the abutments and build a new approach slab to increase the clearance under the bridge by three feet and five inches. The entire project was put in place in just 57 hours, for a total cost of $2.3 million (Pennsylvania Department of Transportation 2016, Sivakumar 2017).

C.26.2 Emergency Planning

No information regarding event planning was found.

C.26.3 Assessment

The original bridge was built in 1930 and used a T-Beam Superstructure design. The bridge had a low clearance of 13’-9” which was deemed too low for larger vehicles, as shown in Figure C-112. Moreover, the superstructure was actively crumbling, and debris was falling through a hole in the deck, making a speedy repair imperative (Ruzzi et al. n.d.).

Figure C-112. Original Bridge (Ruzzi et al. n.d.)

Since there was limited information available about the bridge, a lidar survey of the entire structure was completed. This gave engineers a better understanding of he existing structure, but also provided critical information such as dimensions (Sivakumar 2017). The Lidar scans were processed to develop 3D as-builts for the bridge, and were used to design the new abutment cap, superstructure, and approaches (Ruzzi et al. n.d.). Building information modeling (BIM) was used to convert the lidar data into a 3D model as shown in Figure C-113.

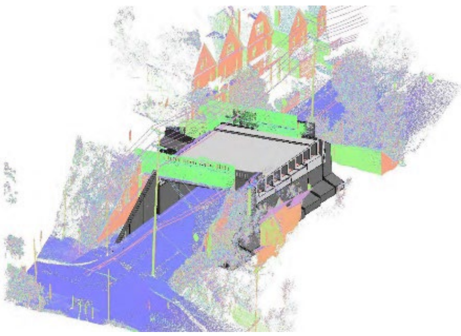

Figure C-113. Lidar Scan (Ruzzi et al. n.d.)

Once a design was generated, the bridge was virtually assembled to check for component fit, and overall construction sequence. The 3D renderings were given to the contractor to assist with construction (Ruzzi et al. n.d.).

C.26.4 Rapid Restoration

C.26.4.1 Permanent Structure

The construction was set to take place over a weekend to minimize traffic disruption. As soon as the bridge closed at 9pm on Friday, demolition began. The abutment was saw-cut along the backside to remove the deteriorated portions, and then the superstructure was demolished, including the approaches. With the debris cleared, the new (and taller) abutment caps were lifted into place. The abutment caps were secured with dowels, and shims were placed to reach the correct seat elevations, as shown in Figure C-114. The gaps created by the shims were filled with rapid set grout via ports. Then, cranes were used to lift the precast modular slabs into place, as shown in Figure C-115. These slabs were made up of steel girders with a composite lightweight precast concrete deck slab. At the same time, the precast approach slabs were also installed. These slabs had a steeper angle than in the original bridge to accommodate the higher bridge span. Lightweight concrete was used for the new bridge to reduce weights required by the cranes. Ultra high-performance concrete (UHPC) was used for the closure pours as shown in Figure C-116. Once cured, the bridge was opened to traffic (Ruzzi et al. n.d.).

Figure C-114. Abutment Cap (Ruzzi et al. n.d.)

In the days that followed the reopening, the abutments were backfilled to better support the bridge loads. Rapid set Latex Modified Concrete (LMC) was placed over the sawcut groves, and epoxy resin was added to the abutment surfaces as a protective coating, as shown in Figure C-117 (Ruzzi et al. n.d.).

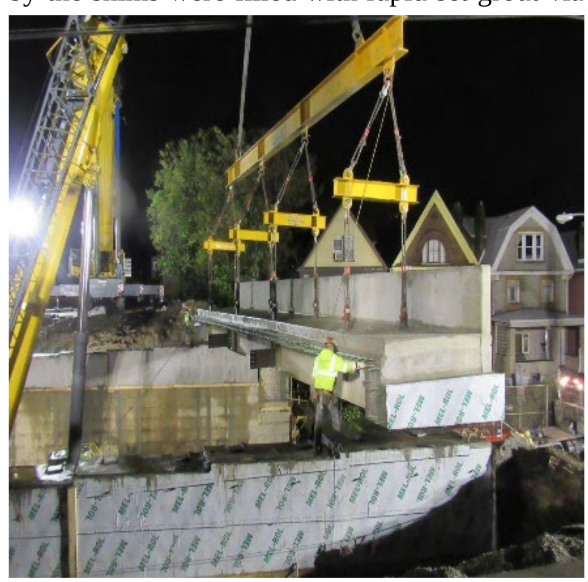

Figure C-115. Installation of Precast Elements (Ruzzi et al. n.d.)

C.26.5 Challenges

The bridge was located in an urban area, with a residential home adjacent to the structure. The limited right of way (ROW) restricted the work area around the bridge, which is one of the reasons why ABC was so appealing to use in the first place. Furthermore, the proximity of overhead powerlines limited the size and placement of cranes for lifting elements into place. Strategic planning was conducted to ensure all equipment would fit on site. On each element, marks were placed to indicate where the piece should be lifted (Ruzzi et al. n.d.).

The bridge's geometry consisted of a curve and skew, making the design challenging. To accommodate the curvature, the center steel composite beams were all spaced at consistent spacings, but the overhangs varied, adjusting as needed to match the roadway geometry (Ruzzi et al. n.d.).

It was difficult to set the precast abutment caps level, even with shims, so investigating another method for setting them in place would help for future projects (Ruzzi et al. n.d.).

Figure C-116. LMC Placement (Ruzzi et al. n.d.)

Figure C-117. UHPC Pouring of Joint (Ruzzi et al. n.d.)

C.26.6 Innovations and Lessons Learned

C.26.6.1 3D Renderings of Construction Sequencing

The 3D renderings and construction sequencing check with BIM was helpful for the project. Even in cases where high quality as-builts are available, BIM should still be encouraged to provide a better visual understanding for the contractor and the workers, as shown in Figure C-118 (Ruzzi et al. n.d.).

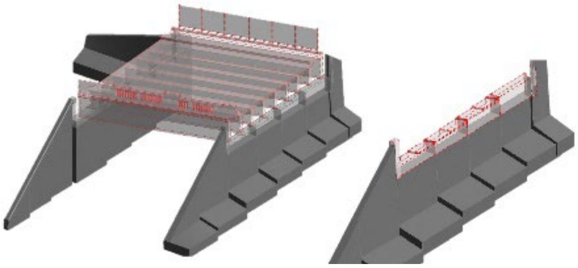

Figure C-118. Building Information Model of Bridge (Ruzzi et al. n.d.)

C.27 Washington ABC I-5/US 12 at Grand Mound 2011 [Other]

Table C-27. Washington ABC I-5/US 12 at Grand Mound

Case Study Name/Date	Washington ABC I-5/US 12 at Grand Mound (2011)
Location	Washington, USA
Event Type	Other
Bridge Name	I-5/US 12 Bridge at Grand Mound
Scope/Costs	Total Bridge Replacement, total cost of $15.52 million
Planning Techniques/Tools	Design-bid-build
Event Response	Diverted traffic to keep vehicles moving during demolition and repair
Assessment Techniques/Tools	N/A
Rapid Restoration Type	Prefabricated bridge elements and systems
Innovations	• Precast columns, pier caps, and diaphragms • Integration of architectural details with precast columns and pier caps • Still met seismic requirements while using precast elements

C.27.1 Introduction

The I-5/US 12 Bridge at Grand Mound in Washington was deteriorated and needed to be replaced. For the replacement option, WSDOT decided to use ABC to reduce traffic impacts, improve work zone safety, and reduce the overall lifecycle cost. The replacement structure used (15) 35" deep prestressed deck bulb tee girders with a 5" cast-in-place covering, as shown in Figure C-119. This was a demonstration project sponsored by the Highways for LIFE program. The University of Washington performed several tests as a proof of concept before implementation, such as the precast column-to-footing connections. Other precast components included the columns, pier caps, girders, and diaphragms. Overall, the new bridge used precast components with cast-in-place concrete joints to create a lasting structure and demonstrated the ability to use ABC technologies on a greater scale (Khaleghi et al. 2012).

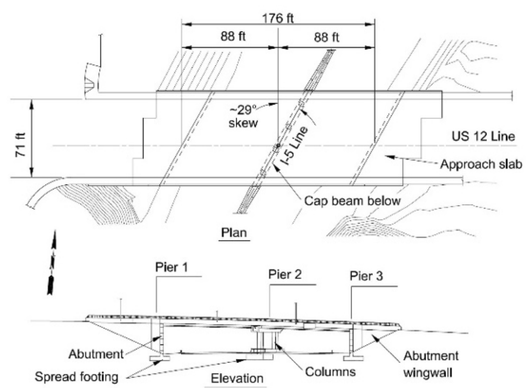

Figure C-119. Plan Drawings (Courtesy of PCI Journal, Khaleghi et al. 2012)

C.27.1.1 Event Response

Traffic was diverted around the work zone to keep vehicles moving and to increase workers safety before the project began.

C.27.2 Emergency Planning

C.27.2.1 Crowdsourcing and Information Gathering

This project served as a Pilot Program for WSDOT to test the feasibility of ABC Implementation, so there was no information collected by the public as part of information gathering.

C.27.3 Assessment

The existing structure was deteriorated and needed replacement – there was no extreme emergency event (i.e., earthquake, collisions, etc.) that led to this decision. Thus, it is assumed traditional assessment techniques as part of routine inspections were used to make this determination.

C.27.4 Rapid Restoration

C.27.4.1 Procurement

The precast components were manufactured off site and trucked to the project. As a test, WSDOT wanted the columns to be cast in segments to see how easily they could be linked together. The columns were short enough to be transported in complete sections, but this may not be the case for larger structures. The bridge components would then be assembled in a socket-style connection highlighted in Figure C-120 (Khaleghi et al. 2012).

Figure C-120. Integrated Footings and Bent Cap with Columns (Courtesy of PCI Journal, Khaleghi et al. 2012)

C.27.4.2 Permanent Structure

Before setting the columns, the region around the bents were excavated, the footing forms were set in place, and the concrete poured. Then, the column segments, which were manufactured off site, were lifted into place and reinforcement bars were added and grouted to create one cohesive unit. The remaining segment of the columns were strung onto the exposed reinforcement bars, in the same fashion as stringing beads on a necklace, as shown in Figure C-121.

Figure C-121. Setting of a Column Segment (Courtesy of PCI Journal, Khaleghi et al. 2012)

For setting the pier cap beam, shims and bracing were set, as shown in Figure C-122. Then the precast beam segments were lifted into place and grout was used to bond the cap beams, column, and reinforcement together. The challenge was the ensure a proper moment transfer from the cap beam to the columns, as further discussed in the following sections. Once the cap beam was lowered, then girders were set, and finally the 5" thick topping was poured. The diaphragms were added after the top slab was cast. Lastly, the sidewalk and traffic medians were cast-in-place, and the bridge was completed (Khaleghi et al. 2012).

C.27.5 Challenges

There was a considerable amount of congestion at the cap beam closure. For this project, there was extra attention to detailing, so this was not an issue, but for future projects, this should still be kept in mind to ensure all the bars line up when the segments are linked into place. Any misalignment with detailing could pose major problems.

Furthermore, another challenge focused on grouting the column segments and ensuring proper closure of the cap beam segments. This was further complicated by the bridge skew. More practice with these types of details and construction, such as joints and finishes, would be needed before mass production of similar-type structures in the field, as warned by the contractor (Khaleghi et al. 2012).

Figure C-122. Setting of a Pier Cap Segment (Courtesy of PCI Journal, Khaleghi et al. 2012)

Another challenge was ensuring the right tolerances were used when setting components. If closures were too tight, the joints were difficult to grout (WSDOT 2016).

Lastly, it was of the utmost importance the beam cap to column connection was fully grouted. This would ensure the proper moment transfer from the girders to the ground. This design simulates a continuous span, but improper detailing would create two simple spans, which would not transfer moment, and distribute the structure loads differently than designed.

C.27.6 Innovations and Lessons Learned

C.27.6.1 Cast-In-Place vs. Precast Columns

One area of trouble was the precast columns. The contractor believed using a single precast column instead of several, smaller segments would be easier to install and save time. This may not be feasible for larger projects, but for typical bridge column heights, a single column would be more efficient (Khaleghi et al. 2012). Moreover, the contractor did indicate the preference of cast-in-place columns over precast but would be willing to switch if required to do so (Accelerated Bridge Construction University Transportation Center n.d.a). Furthermore, it was found that grouting all joints at once for the deck and superstructure was easiest, as a high-pressure pump would ensure all the ducts were adequately filled.

Figure C-124. Narrow Joints (Courtesy of PCI Journal, Khaleghi et al. 2012)

C.27.6.2 Wider Joints

Wider joints made it easier to grout deck joint connection, and using J hook stirrups instead of U hooks for the beam caps would also have made it easier for placement, as shown in Figure C-124 (Khaleghi et al. 2012).

Figure C-123. Architectural Column and Pier Cap Detailing (Courtesy of PCI Journal, Khaleghi et al. 2012)

C.27.6.3 Architectural Detailing

A benefit to using precast over cast-in-place and other traditional methods is the convenience of adding architectural features to the bridges, as shown in Figure C-123 This can be done by the manufacturer at the plant, reducing the field time necessary for such details while still making the structure aesthetically pleasing (WSDOT 2016).

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